LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

Heikki Salkinoja

OPTIMIZING OF INTELLIGENCE LEVEL IN WELDING

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1383 at Lappeenranta University of Technology, Lappeenranta, Finland, on the 4th December, 2009, at noon.

Acta Universitatis
Lappeenrantaensis
362

Supervisor Professor Jukka Martikainen
Faculty of Technology
Department of Mechanical Engineering
Lappeenranta University of Technology
Finland

Reviewers Professor Dr William Lucas
TWI
University of Cambridge
United Kingdom

Dr Petteri Jernström
Levator Oy
Hanko
Finland

Opponent Professor Dr William Lucas
TWI
University of Cambridge
United Kingdom

ISBN 978-952-214-849-0
ISBN 978-952-214-850-6 (PDF)
ISSN 1456-4491

Lappeenrannan teknillinen yliopisto
Digipaino 2009

Corrections found after printing of this book

Reviewer and opponent

Professor Dr William Lucas
The Welding Institute (TWI), Cambridge
United Kingdom

Page 12, Formula (2) ρ= density of filler material [kg/mm^3]

ABSTRACT

Heikki Salkinoja

Optimizing of intelligence level in welding

Lappeenranta 2009
101 p.
Acta Universitatis Lappeenrantaensis 362
Diss. Lappeenranta University of Technology
ISBN 978-952-214-849-0, ISBN 978-952-214-850-6 (PDF)

ISSN 1456-4491

The productivity, quality and cost efficiency of welding work are critical for metal industry today. Welding processes must get more effective and this can be done by mechanization and automation. Those systems are always expensive and they have to pay the investment back. In this case it is really important to optimize the needed intelligence and this way needed automation level, so that a company will get the best profit. This intelligence and automation level was earlier classified in several different ways which are not useful for optimizing the process of automation or mechanization of welding.

In this study the intelligence of a welding system is defined in a new way to enable the welding system to produce a weld good enough. In this study a new way is developed to classify and select the internal intelligence level of a welding system needed to produce the weld efficiently. This classification contains the possible need of human work and its effect to the weld and its quality but does not exclude any different welding processes or methods.

In this study a totally new way is developed to calculate the best optimization for the needed intelligence level in welding. The target of this optimization is the best possible productivity and quality and still an economically optimized solution for several different cases. This new optimizing method is based on grounds of product type, economical productivity, the batch size of products, quality and criteria of usage. Intelligence classification and optimization were never earlier made by grounds of a made product.

Now it is possible to find the best type of welding system needed to weld different types of products. This calculation process is a universal way for optimizing needed automation or mechanization level when improving productivity of welding. This study helps the industry to improve productivity, quality and cost efficiency of welding workshops.

Keywords: welding, mechanization, mechanized welding, automated welding, optimizing of intelligence, robot welding, adaptive welding, quality control.

UDC 621.791 : 681.513.6 : 621.865.8

PREFACE

The inspiration for this dissertation came under European Welding Engineer course number 14 held in Lappeenranta University of Technology (LUT) during winter 2002-2003. A part of this dissertation was done as a part of research projects “Heatex” and “Vyyt” founded by EU under years 2006-2009.

I am grateful for the supervisor of my study, Professor, Dean Jukka Martikainen for his really fine guidance and support during the course of this work. His advice has greatly helped me professionally in my daily work as a lecturer, too.

I wish to thank the pre-disputation examiners, Dr Petteri Jernström, Levator Oy and Professor Dr William Lucas, TWI Cambridge for their guidance and valuable comments.

I would like to express my sincere thanks to the persons who made this work possible: Docent Antti Salminen, Professor Heikki Handroos, Lic. Tech. Raija Lankinen, M.Sc. Ilkka Korhonen, M.Sc. Reijo Kuivalainen, from LUT and M.Sc. Markku Sinkkonen, Aduser Oy/Heatex-project, B.Sc. Jouko Keinänen, Sahala Högfors Oy, MD Asko Vainionpää, Seinäjoen Laatuvaruste Oy, MD Jukka Setälä, Retco Oy, M.Sc. Ismo Meuronen, Meurotec Oy, M.Sc. Hannu Blomqvist, VR, MD Arto Koljonen, Savon Putkihitsaus Oy, Dir. of Technology Osmo Heinonen SP-Putki Oy and special thanks to M.Sc. Juha Lukkari, ESAB Oy.

Special thanks go to my closest family, my daughter Johanna Kokkonen and her husband Janne Kokkonen, my son Pekka and his fiancée Jenni Heinonen and younger daughter Minna and her boyfriend Jani Jutila for special help with computers.

The greatest thank I have to give to my wife Eeva-Liisa, because for all these years she has been the greatest motivator for this thesis and the biggest support for me.

This thesis is dedicated to my deceased parents Aino and Niilo, who were able to support me till the end of their lives.

Lappeenranta, November 2009

Heikki Salkinoja

CONTENTS

SYMBOLS AND ABBREVIATIONS

a	factor in equation (4)
AC	alternative current
AISI	American Iron and Steel Institute
AVC	Automatic Voltage Control
A_w	sectional area of weld
B.Sc.	Bachelor of Science
CCD	Charge Coupled Device
CCPC	Central Control Computer
l	length of weld
D_C	duty cycle
D_r	deposition rate
Double pulse	pulsed alternative current in welding torch has higher frequency smaller pulse width
EB	Electron Beam Welding
EN	Euro Norm
IWFMC	Intelligentized Welding Flexible Manufacturing Cell
IGSCC	Intergranular Stress Corrosion Cracking
IP	Image Processing Interface
ITER	International Thermonuclear Experimental Reactor
IWR	Intersector Weld/ Cut Robot
LB	Laser Beam Welding
LCD	Liquid Crystal Display
m_w	weight of weld
MIG	Metal Inert Gas Welding
MAG	Metal Active Gas Welding
MMA	Manual Metal Arc Welding
MPPC	Manipulator and Positioner Control Computer
NOMAD	Autonomous Manufacture of Large Steel Fabrications
NDT	Non Destructive Testing
PA	flat position
PAW	Plasma Arc Welding
PB	horizontal vertical position
PC	horizontal position, personal computer
PD	horizontal overhead position
PE	overhead position
SAW	Submerged Arc Welding
SFS	Suomen standardisoimisliitto SFS ry
SP	Signal Processing Interface
t_{set}	setting-up and taking off time of welding equipments
t_{tw}	total welding time
TIG	Tungsten Inert Gas Welding
WP	Welding Power
WPPC	Welding Power Computer
WPS	Welding Procedure Specification
ρ	density
1-D	one dimensional
2-D	two dimensional
3-D	three dimensional

2T	MIG/MAG welding machine feed filler wire all the time the trigger is pressed
4T	MIG/MAG welding machine start to feed filler wire when the trigger is pressed the first time and stops when pressed the second time

1. INTRODUCTION

1.1 Background

The welding of critical constructions is a demanding job for metal industry. Quality must fulfil requirements and standards. Efficiency, productivity and net profit should be high and in the global markets there is severe competition. The reliability of products must be 100 % and failures may cause fatal damages. The operational safety of products must be high and severe faults of welds can be fatal too. A solution for this problem can be higher mechanization and automation level and increasing of intelligence in welding method.

The amount of this intelligence must be optimized, because labour costs are here extremely high and on the other hand, more intelligence in the process makes it more complicated, sensitive to disturbances and using it becomes a demanding job. If there is too little intelligence, there is among other drawbacks a high amount of manual work, risk of welding defects, repair work and lower quality. On the other hand if there is too much intelligence and automation, costs jump up and the complexity of the system increases a lot, the requirements of maintenance change totally and the requirements of the staff professional skills increase. Welders must become from professional welders to professional operators who know welding and automation and they often have at least B.Sc.-level degree in engineering etc. or higher education.

Modern manual welding power units have internal systems which can optimize welding parameters according to a few given values like material, weld type and size like construction steel and filled weld with designed throat thickness. This means only that a welder does not need to estimate some parameters. On the other hand the quality requirements of welding standards define that in WPS (Welding Procedure Specification) given welding parameters must be used. The professional skills of a welder naturally contain the ability to select welding parameters, but the manual making of welding work, welding torch movement and right filling of a groove are the most difficult things when making a weld. If the welding system has in-built intelligence and ability to find the beginning and end of the weld groove, transport the arc well and it can control the pool with the right amount of filler material, it is much more effective and able to compete today.

1.2 Contribution of the dissertation

In this doctoral thesis, what is studied is the welding of critical components, like pressure vessels and heat exchangers of process and power plant industry and one critical case from transport equipment industry to optimize the intelligence level of a welding system. Also common repair welding applications are studied.

The earlier classifications of the intelligence of welding systems are based partially on the technical and partially on the functional differences of machines. They divide work into two classes which are made by a person and made by a machine or classify systems according automation levels, but do it quite well in seven levels. It is a little too finely made classification for internal intelligence of a system if we are building a method for optimizing that level. In this discussion intelligence of welding is defined as ***the system ability to produce a weld which will fulfil the requirements***. It contains the exact seam finding, seam tracking, arc controlling with the right amount of filler feed and controlling of a weld pool to make a good weld with the exactly right amount of filler material. Principally these things do not speak out or presuppose anything from technology. These abilities are the most critical things a manual welder must master for example in TIG or MMA processes and the same abilities fit for automated or mechanized welding too. The amount of intelligence levels must be small enough and classification of all different welding systems must fit in some of these classes. Only in this way it is possible to optimize intelligence on basis of productivity, economy and quality requirements.

I argue that in this type of critical welding application, the amount of intelligence in welding systems can be optimized on the grounds of economical productivity, batch size of products, quality and criteria of usage.

By calculating the best optimum of intelligence for a welding system it is comprehensively possible to improve the result of welding work. This includes both the achieved measurable quality of a product and also the profitable production with the ergonomic aspect of workers and surroundings. In each case, it is possible to optimize the best level of intelligence to use in this special case.

1.3 Objectives of the dissertation

The original objectives and contribution of this thesis to the science and technology of welding are:

1. To develop a totally new and comprehensive way to classify intelligence levels of welding systems.

2. To define all those factors, which have effect for the selecting and optimizing process of the intelligence level of the welding system

3. To develop a new, comprehensive method to optimize and select the intelligence level for the welding system which will be invested.

With this method it will be possible to get a better profit and better productivity for welding industry. Today this optimization has a really big effort for the economical result of the companies which make welded products. The new system developed must take into account weld, product, welding process, working conditions, quality, system reliability and total economy when calculating the best intelligence level for each welding case. This new optimizing method is based on economical productivity, batch size of products, quality and criteria of usage. This method takes into account the special features of products, which has not been done before.

2. PRODUCTIVITY, QUALITY AND ECONOMY IN WELDING

2.1 Productivity in welding

Productivity in welding depends among other things on the efficiency of machines, arcing time, deposition rate, setting time of machine, preparation work of welds and accuracy of parts. The professional skills of welders are one of the most important things in productivity. One often forgotten thing is doing of things in a factory. How systematic and careful is the working style in a factory? Of course there are many other important things affecting productivity, but these are the most usual ones which can be improved more or less in an easy way by automation, mechanization and improving the intelligence of the system. Normally increasing automation and mechanization decrease the amount of manual welding work and workers but increase the setting time, preparation work and requirements of accuracy in parts coming to weld. Often the batch size is not big enough for cost effective investment and work is done manually although there are more effective systems available. The improving of productivity in a company is a comprehensive process which must cover the whole organization. Barkhoff has presented the five welding do's that must be made to improve productivity of welding work in a company. This method is called Total Welding Management and these five principles are (Barkhoff pp. 65-70)

1. Reduce weld metal volume
2. Reduce arc time per weldment
3. Reduce rejects, rework, and scrap
4. Reduce work effort
5. Reduce motion and delay time

This example shows all the things that can be done to improve productivity and profitability of welding work in a company.

According to Cary advantages of automatic welding include the following (Cary p. 289):

1. Increased productivity through higher operator factor
2. Increased productivity through higher deposition rates
3. Increased productivity through higher welding speeds
4. Good uniform quality that is predictable and consistent
5. Strict cost control through predictable weld time
6. Minimized operator skill and reduced training requirements
7. Operator removed from the welding arc area for safety and environmental reasons
8. Better weld appearance and consistency of product

Welding time can be estimated by dividing mass of weld by deposition rate and duty cycle and then adding set-up time and take-off time of equipment. Now we have to remember manual welding time of sealing run, but it can be calculated in the same way for both cases. So automate equipment shall earn itself under filling runs.

Total welding time can be calculated by Equation 1

$$t_{tw} = \frac{m_w}{D_r D_C} + t_{set} \tag{1}$$

where
t_{tw} = total welding time [h]
m_w= weight of weld [kg]
D_r = deposition rate [kg/h]
D_C= duty cycle
t_{set} = setting-up and taking off time of welding equipments [h]

Weight of weld can be calculated simply by multiplying the volume of weld by the density of steel

$$m_w = A_w \times l \times \rho \tag{2}$$

where
A_w = sectional area of weld [mm^2]
l = length of weld calculated along the centre of gravity in circle weld [mm]
ρ = density of steel 0.00785 [g/mm^3]

The deposition rate of a manual welder with MMA can be estimated to be some 3 kg/h and automatic or mechanized welding with MAG or SAW some 5 kg/h or more, depending on the current level the machine can use. The welding process and filler materials have their own effects on productivity by deposition efficiency which may vary from 55 % to 65 % by 355 mm long MMA electrodes to 95 % to 99 % by bare solid wire of SAW. (Welding handbook, Vol. 1, p. 494)

What is critical is the welded volume per year and this depends on what sales can sell and where these machines can be used in production. It is not said that machines must only be used in certain welds of certain objects. They may be suitable for many other purposes too.

In the next example of circle welds, a mechanized machine can be used in several types of circular welds in any products, if the diameter of weld is suitable for the machine. In the next case we compare MMA and mechanized SAW. Now we can assume that both cases have similar pre made sealing run. In mechanized welding the set-up time is 15 min and the deposition rate with typical duty cycle is at least 5 kg/h and in manual welding the deposition rate with the typical duty cycle is about 3 kg/h. The typical duty cycle of MMA is about 15 – 30 % and mechanized SAW it can be even 80 -90 %, but in this case it is included in the deposition rates, which are measured in this specific company of case 3 earlier and approximations consist now both the deposition rate and the duty cycle. Because we have no set-up time for a manual welder we get the total produced mass of weld welded for manual welding

$$m_w = D_r t_w \tag{3}$$

where
m_w = total mass of weld [kg]

D_r = deposition rate of welding [approximation 3 kg/h]
t_w = arc time, slag removing and change of electrodes etc. [h]

and for mechanized welding

$$m_w = D_r t_w - a \tag{4}$$

where
D_r = deposition rate of mechanized welding [approximation 5 kg/h]
a = factor, depending on set-up time, now lost deposition 5 kg/h x 0,25 h=1,25 kg by set-up of 0,25 hour = 15 min

These lines cross at time value 0,625 h which is 37.5 min and means mass of filler metal 0,625 h x 3 kg/h=1,875 kg like shown in Figure 2.1.

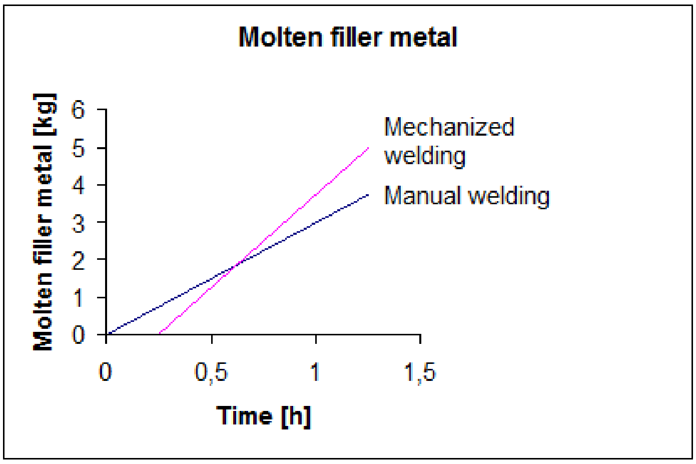


Figure 2.1 Productivity of molten filler metal of manual welding and mechanized welding

With this method we can calculate the critical volume of weld and the approximate needed yearly amount of production for profitable investment.

2.2 Economy in welding

The weld must be made in the most economical way to get the maximum profit. In Finland this means minimizing the manual work and this way maximizing productivity. Normally designing has a big effect to this. Because designing costs are part of production costs, fatal errors are made by saving in designing time. When designer must do quick work, he cannot calculate the optimum thicknesses of welds in every place and select the definitely safest solution. Normally this means much more volume in welds and more expensive welding. For example compressive loaded welds are normally welded to balanced strength with the surrounding construction even when it is not necessary. The higher intelligence of welding system may help to reduce or compensate the high welding costs caused by non-professional design which may be in the driver´s seat when WPS is selected.

Welding costs can be calculated with high accuracy when the following costs are known (Lukkari p.58)

Welding consumables
- filler materials
- welding gases
- welding flux

Manufacturing costs
- work
- energy

Machine costs
- capital costs
- maintenance

A manual welding working hour is so expensive in Finland that this work is more economical to buy from countries with lower labour costs, like Estonia and Russia. Even after transport costs it is still cheaper to make in there. Only the cases in which a company can sell a product with profit seem to be the ones with the total delivery with a “turn key”- principle.

Erkki Uusi-Rauva has collected a model for analysing of profitability according several variables which have their own effect to the profitability. This model is presented in Figure 2.2.

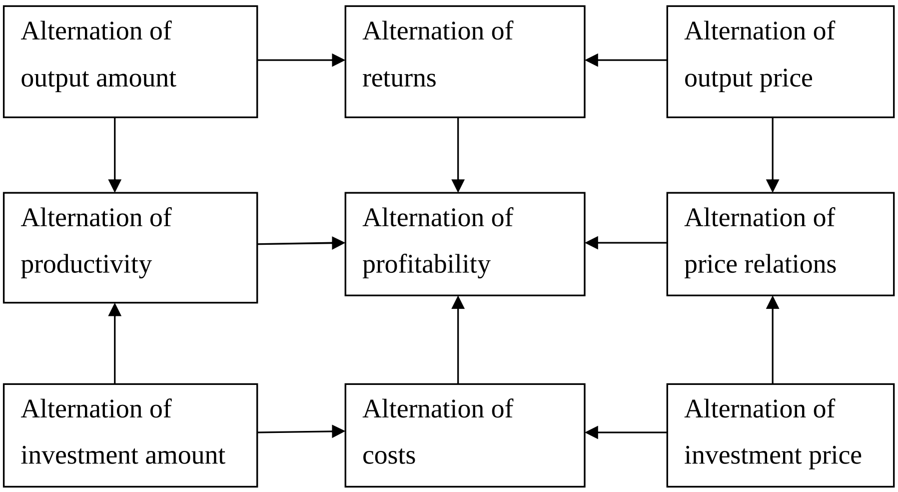


Figure 2.2 Variables of profitability (modif. Uusi-Rauva p. 32)

2.3 Quality in welding

The quality in welding is normally understood to be the quality of welds and fulfilling the standardized quality levels of welds. This is a narrow interpretation of quality. Quality in welding contains all quality from the product specifications of quotation to the use of the product by a customer or an end-user. All the specified requirements of welds have effect on how they must be welded. Sometimes there is a requirement for welding process, like EB or LB, which means automatic welding with expensive systems. Mainly there are no special requirements and the manufacturer may use the process which is just the easiest for him. Both cases can fulfil the quality levels of standards. The main problem can be to keep the level high enough all the time during daily work from year to year.

In most cases automation and mechanization just make a weld surface smoother and reduce roughness and unevenness which are typical for manual welding. A manual welder cannot transport a torch and arc with such a constant speed that the result would be as good as the mechanized transport has. This difference can be seen easily from the weld. The second important difference is, that welding with absolutely constant and well controlled parameters including arc length, ensure the melting of the edge bevel and penetration. Still this does not guarantee that the weld that has been made mechanically is better than the manually made one. There is even a comparative test where the result was that manually made welds had better fatigue life than mechanically made. This result is shown in Figure 2.3. A probable reason was that the welder follows and keeps view of the arc and molten pool. Now he can be sure that the filler wire and base metal will really melt together. A machine had no adaptive intelligence required for this. This just means that automatic welding is not always better than manual.

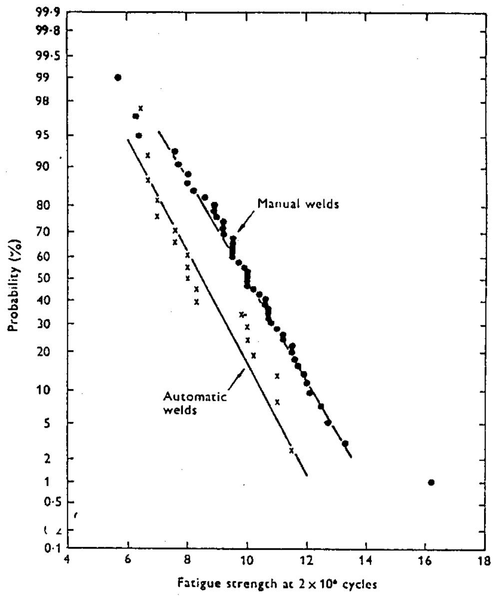


Figure 2.3 Fatigue test results between automatic and manual welds (TTKK/IIW)

Distortion is greatly influenced by design, method of welding and heat input. Thermal distortions in manual welding result from too high heat input in the weld and base metal. In welding energy and thermal efficiency calculations TIG process efficiency is in SFS-EN 1011-2 only 0.6, for SAW even 1 and for MMA it is 0.8. The measured values vary for TIG between 21-48%, MMA and MIG/MAG process between 66-85 % and with SAW 90-99 %. (Lancaster p.158, Christensen & al, pp.54-74).

This explains how much from the welding energy is going to the weld and base material. In SAW thermal distortions are probably smaller at the same cross section area of weld than MMA. The reason is simply that according Lukkari in MMA process 45 % from heat is conducted from the weld to the base material and 10 % stay to pool when in SAW process these values are 8 % from weld to base material and 44 % to the pool. The rest of the energy is going to the filler metal, flux powder and in the air. In SAW energy is used better for melting than for heating. (Lukkari p. 68)

2.4 Interaction between productivity, quality and economy

The main reasons for mechanizing and automation in welding are for example

-Lack of skilled workers
-Welders are coming to retirement age
-Better working conditions and ergonomics
-Easier to reach joint preparation
-Repeatability of welding is good
-Good control of heat input
-Longer arc time without interruptions
-Remote control possibilities
-Video etc. control possibilities
-Better deposition rate and efficiency
-Better and uniform quality

Productivity must get higher, quality requirements must fulfil but not overfill and profit must be gained. Theoretically this is a simple rule to follow. Practically everything depends on everything, and the improving of quality may lower productivity etc. The system must get balanced so that all requirements are fulfilled. Intelligence in welding systems will help to reach technical and productive requirements more easily and more quickly. On the other hand, investment costs get too high easily and economical problems are close. Automation will increase the quality of welds and the productivity of welding work if the investment is economically justified. Rantanen has written about the definition of term productivity in his paper. (Rantanen)

One way to work on improving competiveness is optimizing the intelligence and its level. Especially in the future it is becoming more and more important to make systems more effective and more productive and the lack of skilled workers with high labour costs must be compensated with mechanization, automation and more intelligent systems. The higher intelligence level of the system in the future is becoming a more and more important way to rise to the challenge given by other countries with lower labour costs.

3. INTELLIGENCE TODAY IN DIFFERENT WELDING SYSTEMS

3.1 Background and definitions

A good manual welder is the most adaptive welding system that can be found. A manual welder is nearly independent from the weld type or welding position, makes good weld in a workshop, assembling site and even under the water and other difficult places. But manual work has high price especially here in western countries, productivity is low and welding is not the most comfortable or healthiest work. These are some reasons why welding work is automated and mechanized as much as possible.

Intelligence in welding in this thesis is defined to be the ability of a welding system, machine, equipment, robot etc. to produce acceptable weld in a piece as automatically as possible so that more intelligence needs less work from the operator to manually steer or control the system and especially guide the arc along the joint and correct the arc to overcome deviations.

It can include the adaptive handling of the inaccuracy of bevels and the pre work of parts and the volume variation of the weld groove, all welding parameters or just a travel of a torch along a given line.

The intelligence levels of welding system in this discussion are classified roughly in five levels emphasizing the welding torch movement, seam finding and controlling of the weld pool. (Compare page 45)

1. ***Manual welding and semi-automatic welding in which the welder undertakes all the operations including tracking the joint, manipulating the welding head (gun or torch) and controls the behaviour of the weld pool to accommodate the variations of the joint.*** For example old MMA-transformer and MIG-MAG-welding and modern manual welding power sources with in-built pre-set welding values belong to this category. Flexibility is now maximized.
2. ***Simple mechanisation in which aids are provided to assist the operator, for example a simple track to traverse the welding head (gun or torch) along the joint but the operator is required to control the behaviour of the weld pool by adjusting the position of the welding head (gun or torch) and the speed of travel.*** Seam tracking can be made mechanically by a guiding bar, rollers etc. Power sources may have an internal parameter library to adapt it for a certain material, weld type and plate thickness. Welding carriages belong to this category. The machine itself is still blind and does not react for any obstacles of a piece but drives against it if the operator doesn't react. The system needs to be controlled visually by the operator. A typical, standard type welding boom and column belong to this level.
3. ***Intelligent mechanized system in which aspects of welder skill are included for example, welding head (gun or torch) oscillation to give tolerance to variation in joint gap to facilitate positional welding, but the operator may be required to control the behaviour of the weld pool, for example by adjusting the position of the welding head (gun or torch) and the speed of travel.*** The most modern sophisticated types of

welding boom and column, orbital welding systems and other welding without adaptive properties but with arc length control etc. belong to this category. The operator still may define the beginning and stop point of the weld. Sometimes a camera assisted arc can be followed by the operator.

4. ***Pre-programmed automatic welding operation with no requirement for the operator to make adjustments to the welding parameters to control the welding pool.*** Still modular features of welds. The programme defines the beginning and end points of the weld. There is no vision system for automatic guiding of the beginning and end the weld.
5. ***Automatic welding operation with sensors for adaptive control with no requirements for the operator to make adjustments to the welding parameters to control the weld pool.*** Weld recognition and camera assisted adaptive systems which can sometimes automatically find the beginning and end of the weld and have seam tracking etc. systems. The batch size may be even only 1 when adaptive welding allows flexibility for products like direct programming from 3-D drawings made in computers. Products may have some limiting features, like welding of stiffeners in ship wall plates. The programme may be able to optimize productivity and quality according to measured data.

3.2 Manual welding

3.2.1 Welding processes and methods

Manually used welding processes are normally MMA, MIG, MAG and TIG. These processes are mainly old and well known. They are sure and the quality of welds depends very much on the welder. The productivity of these processes is low because of low deposition rate, especially in TIG-welding.

3.2.2 Practical solutions

Manual welding has the best adaptability and flexibility in variable situations of production work. It has very low productivity and high labour costs compared to automation or mechanized welding processes. Also the quality of welds is circumstantial and depends much on a worker. Still it is the only possible method when welds are not suitable for automation or mechanization or the amount of welds is not big enough for the investment in production automation. Intelligent welding is expensive and needs a good utilisation rate. This means that manual welding remains still the most common method in the world.

A modern welding machine is not only a simple transformer, rectifier or some kind of a generator. There must be a built-in versatile integrated process control system to optimize the welding parameters and it has excellent properties to adjust and reshape the AC-current in welding. There can be several possible processes like MMA and TIG in the same machine, like in Figure 3.1.

Figure 3.1 Modern TIG/MMA welding power source (H.Salkinoja)

Typical modern adjustable properties in a MIG/MAG- welding machine of today are

- Pulse of current
- Pulse of wire feed
- Double pulse (pulsed current has extra pulse with higher frequency)
- Gas flow test (wire feed is off, gas flow on)
- Adjusting of arc dynamics
- Synergic adjusting of welding parameters from one of few knobs, worker just selects the material and plate thickness, machine selects the rest of parameters automatically.
- Display of welding parameters
- Storage memory of used welding parameters
- Data monitoring and registration of welding parameters, time etc for quality control
- PC-connection.
- Self testing programmes for machine, etc.

The next list is one example from a modern welding machine (Kemppi);

- selection of welding process: MMA, MIG 2T (filler wire feed on as long as the trigger of the torch is pressed), MIG 4T (filler wire feed on by the first pressing of the trigger and off by the second pressing) current switching selection of MIG/MAG, synergic MIG/MAG or synergic Pulsed MIG
- Materials, gas and wire diameter selections for synergic welding
- Controls and displays of the main welding parameters: wire feed speed or MMA current, voltage, welding dynamics, plate thickness display
- Selection for controls: local controls, gun remote control unit, remote control unit
- Special features of MIG/MAG and Pulsed MIG processes selected from panel: creep start, hot start, crater filling
- Cable and gun lengths of welding circuit can be taken into consideration by the calibration function

- Parameter presetting of MIG/MAG, 1-MIG and PulsedMIG welding can be changed by using the SETUP function

It is possible to register and analyze welding values and weld quality easily with data registering programmes. This type of a program is available to the most sophisticated power sources of welding machine manufacturers and it receives and controls data by the serial port during welding through PC-interface. The programme can display welding data, draws in real time graphical form: voltage, current, wire feed speed and wire feed motor current. It also calculates welding energy, heat input, wire consumption and the welding costs like gas, filler material, energy, labour and total costs. This programme can be used as an excellent tool also for creating WPS (Welding Procedure Specification). Hierarchy in program structure guarantees that an individual weld is easy to trace and individual files can be seen clearly in the PC display, so it is simple to control the jobs and welds. (Kemppi)

From MIG/MAG-process several new variations are made by different manufacturers such as (Suoranta p. 18-21)

1. Modified short arc, 5-6 manufacturers on market
2. Self-adaptive arc, 2-3 manufacturers on market
3. Pulsed arc:
   - traditional pulse
   - double pulse
   - combination of different pulse shapes
4. Alternative current

The common target of all modified short arc versions is the exact control of filler metal transfer and minimizing of heat input. This is made by controlling the current according to different arc phases like under burning and short circuit. The common advantages of these processes are lower heat input than traditional cold arc welding, no spatter, welding of very thin materials, joining of different metals and controlled welding of sealing pass. the adaptively controlled arc gives advantages like controlling with one knob, stable arc independent of worker and less spatter. The pulsed arc has less spatter, lower heat input, good visual appearance and reduction of pores. It is used especially in the welding of aluminium but it is becoming more common in the welding of steel.

The most modern versions of MIG/MAG power sources just coming on markets, have an in built real-time penetration control system based on real time welding power control by adjusting welding parameters, which allows bigger variation for electrode extension of the welding torch. (Peltola, Abstract)

By combining different pulses it is possible to improve MIG/MAG-process further in aluminium welding. We can mention one example which minimizes the heat input, controls the welding of sealing pass and thin materials by pulse with the short arc and by pulse with the hot arc maximizes productivity.

Alternative current can be used in aluminium welding because it has similar advantages to TIG, like the cathodic cleaning of oxides, good visual quality and controlling of penetration combined with MIG advantages smaller heat input and better productivity.

3.3 Mechanized welding

3.3.1 Welding processes and methods

In mechanized welding MIG, MAG, SAW, PAW and TIG processes are normally used. For mechanized welding it is typical to use continuous travel of arc along the weld groove. Also it is usual to use continuous filler wire and more productive processes. The transport of arc is made by moving a torch along the welding groove or moving the piece in proportion to the torch or exceptionally moving both the piece and torch. Pieces are moved normally by rotating table or rollers with adjustable rotation speed and torch may have different types of transport carriages. These systems are blind for obstacles coming on their travelling way and they will collide together if the operator doesn't react.

3.3.2 Practical solutions

The mechanization of straight welding travel can be done by welding carriages guided with rail as shown in Figure 3.2 and even battery operated carriages like in Figure 3.3 These systems can be equipped with a welding torch oscillation mechanism. As a modern detail, they may have a magnetic holder, so that vertical and horizontal transport and even overhead welds can be done without the guiding rail. The most effective deposition rate of carriages can be achieved by SAW-process shown in Figure 3.4 and there may be two welding heads in the same carriage.

Like in Figure 3.2 it is shown that there are only mechanically reproduced movements made by electric motors or pure mechanically controlled travel of carriage but no in-build intelligence at all. These types of machines are blind and drive only according to given parameters like travel speed and oscillating width until someone will stop the machine. There is no adaptive control of machine or any kind of measuring operations. In this case the magnetic actuator is a typical world beater because other carriages do not have this system yet.

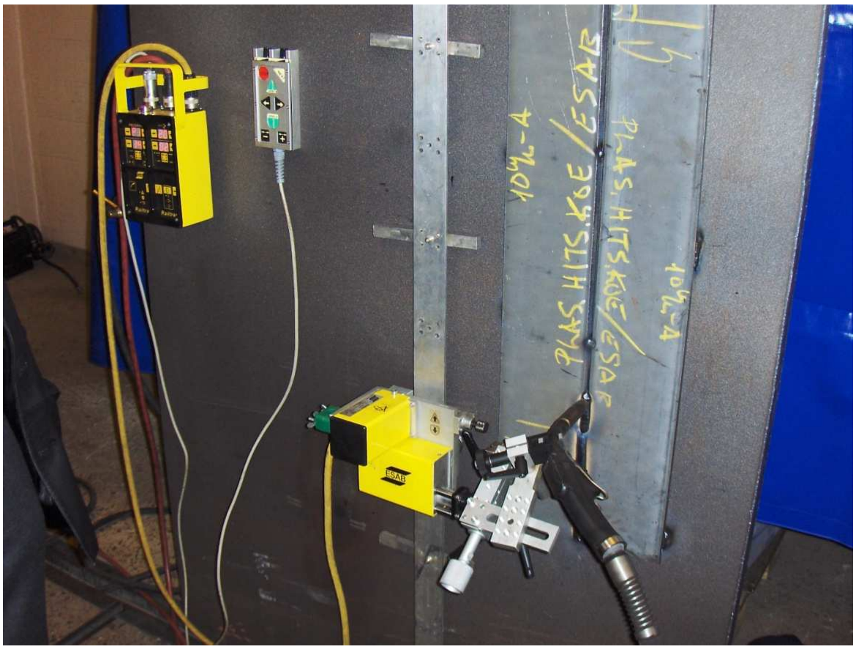


Figure 3.2 Rail guided welding or cutting torch carriage (H.Salkinoja)

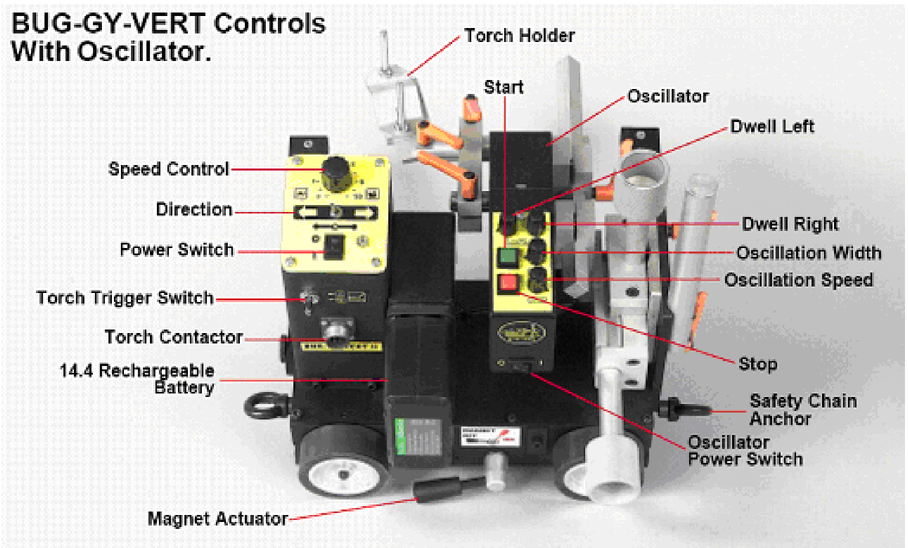


Figure 3.3 Battery powered, with modern magnetic actuator equipped with travel carriage for welding in vertical or horizontal position. (BUG-O)

Figure 3.4 SAW travel carriage (AWP)

The second way to mechanize arc travel is to move the piece and keep the torch fixed. These machines are mainly rotating tables and rollers or some kind of rails and wagons to transport welded part rectilinearly. These machines work exactly in the same way as a simple electric motor with continuous speed variation and there is no higher intelligence in the machine. Figure 3.5 shows the typical movement possibilities of a welding positioner.

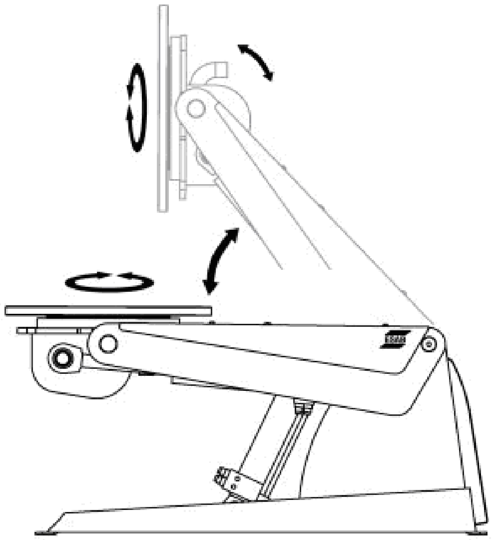


Figure 3.5 Motorized positioner and its movements (Pema)

Automated circle burning and welding of pipe and pressure vessels is an interesting application on welding mechanization. The quality requirements of the surface and straightness are tight and the orders of the authorities give their own requirements for work. Work must be productive too. Welding automates are faster than a manual welder if material thickness is big enough and the volume of the weld increases high enough. The root must normally always be made by hand because machines are not yet reliable enough to make a good root pass. Then the higher deposition rate of automate compensates the higher setting time of the machine. On the other hand the accuracy of the edge bevel in mechanized welding must be much higher than manual work. The branch T-saddle welding of a pressure vessel is a challenging job. Bevel cutting and weld are not circumferential but the saddle form and cutting are difficult to do manually. If the angle of the body and branch pipe centrelines is 90 degrees, it is easier to mechanize the cutting of bevels and the welding of branch. The cutting work can be done with a mechanized circle cutter and a welder like a machine made in Japan in Figure 3.6.

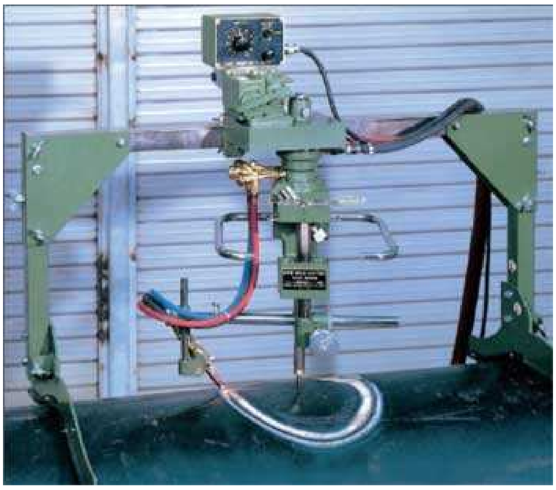


Figure 3.6 Mechanized circle cutting machine (Koike)

The cutting machine is normally equipped with a flame or plasma cutting head. The machine has a simple mechanically adjustable rise and fall cam system to follow the saddle line and keep the torch at the right height from the saddle surface. A similar crank system is in the American circle welder which is shown in Figure 3.7.

For pieces with big dimensions special type welding automates are built. A gantry type machine is suitable for long components and in Figure 3.8 a tailored application with two SAW welding heads for the welding of beams is shown. Typical components are more than ten meters long box beams and it is possible to make two welds at the same time.

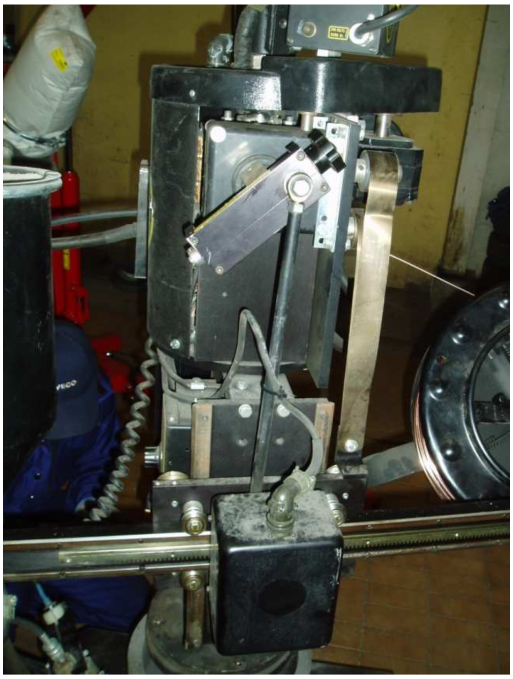


Figure 3.7 Saddle line follower rise and fall cam of a circle welder (H. Salkinoja)

Figure 3.8 Welding gantry with two SAW-welding heads (ESAB, Lukkari)

One common standard machine type is a column and boom combination where one or two welding units are assembled at the end of the boom as shown in Figure 3.9.

Figure 3.9 Welding column and boom (H.Salkinoja)

They are typically used with turning rolls in welding of big cylinders like in evaporating plant or other process industry equipments. These types of machines can use several welding processes and the most common process is SAW because of its high deposition rate and productivity. Basic control system for SAW consists of the following (Welding Handbook, Vol 2, p. 261):

- Wire feed speed control
- Power source control for voltage or current
- Weld start/stop switch
- Manual or automatic travel on/off switch
- Cold wire feed up/down

They have normally no more in-built intelligence than a rail tracking. That can be made with a mechanical, electromechanical or optical principle. Because of a very long lifetime (even several decades) of the column and boom constructions, the oldest rail tracking in SAW-process may only be a light spot and operator must steer the machine and keep it at the right position in joint preparation. The disadvantage of this system is that the operator must be close to the arc to control it as shown in Figure 3.10.

With computer vision it is possible to steer the arc position automatically in the weld groove. When writing this dissertation, there is a process development of an adaptive control for adjusting wire feed according to the measured value of the weld groove volume. The main principle is that the operator can work on the floor level when the arc is burning in several meters' height.

On the market there already exists a welding column and boom where the horizontal boom is telescopic to save the floor space when welding in low positions. This unit has several programmable controllers steered by one industrial computer. All welding and steering parameters are controlled by this computer. There are two normal video cameras and the computer vision connected to this system so that the operator can follow the welding process. The computer has a Windows based user interface. The system uses the pulsed SAW process where productivity and penetration can be optimized by pulse parameters

Figure 3.10 Working with a welding column and boom using laser pointer as locating mark for SAW arc when welding the inner side of a big cylindrical piece. (H. Salkinoja, courtesy of Saarijärven säiliövalmiste Oy)

3.4 Automated welding

3.4.1 Welding processes and methods

In automated welding there are normally welding processes used without a filler wire like melting with TIG, plasma, laser or electron beam and when it is needed, filler metal processes with continuous filler wire. Processes are normally MIG, MAG, SAW, TIG, PAW, LW, EB and hybrid processes. Systems have normally an automated process programme and operator just to keep watch that the system works.

3.4.2 Practical solutions

Orbital Welding

Orbital welding is taken under closer inspection because it is a very good example of intelligence levels 3 or 4 in the modern mechanized welding of demanding and critical process components. Orbital welding is specified as a process where normally two pieces, like tubes, pipes or tube with tube-sheet will be joined together with an arc travelling circumferentially around the piece. It is very useful because of the excellent quality of welds, repeatability and because it does not need excellent manual welding skills. The weld is smooth and also has good food hygiene level. This welding method is used for instance in

-Food, dairy and brewery industry
-Chemical industry
-Medical industry
-Process industry
-Power plant industry
-Nuclear power plants
-Space industry
-Shipyards
-Furniture industry
-Military applications

Orbital Welding belongs to semi-automatic-welding processes and normally it is a programmable process where an electric welding head rotates the arc automatically round the piece and all welding parameters are taken from the computer's library and the whole process works along the programme of the computer. Working parameters are empirical and stored in the computers' hard disc or some other data carrier. The operator will take suitable parameters for each material and tube size beforehand from the library. This system is totally blind for all changes in the joint preparation. Normally a computer can follow and adjust only parameters of the arc, like voltage and current and in this way the height of electrode from the pool to keep the process in given limits. Welding speed or oscillation etc. parameters can be changed only manually under the process or they are fixed.

In orbital welding the possible process is normally TIG with or without afiller wire, MIG, MAG or PAW process. For bigger diameters vertical pipes and cylindrical containers SAW process for horizontal weld is used. In Figure 3.11 the principle of the TIG-hot wire process is shown. The filler wire is now heated by electric current before it goes in the pool.

Because of the control of the pool and the better quality of the weld, the filler wire feed to the pool is normally before the arc. The orbital welding unit consists of a welding head, a welding power source equipped with an internal or external steering computer, cables, cooling- and gas-systems.

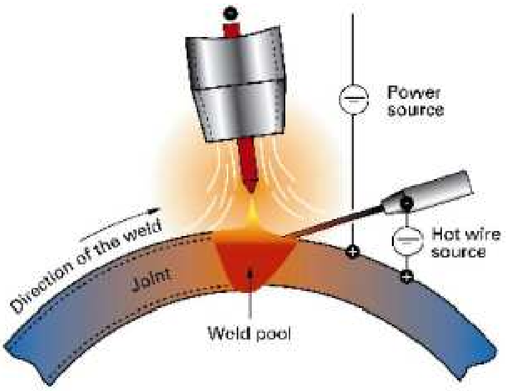


Figure 3.11 TIG-hot wire process (Polysoude/Meuronen)

Welding head

There are four main types of welding heads. These types are closed heads and open arc heads for tubes and pipes and a welding track for bigger diameters. The last main type is made for the tubes on the tubular sheets of heat exchangers. Others are mainly tailor-made systems.

Closed welding head will be fixed around the piece and it will give a full protection for an arc. Typically a manufacturer makes a few closed welding head assortments for certain tube diameters like in Figure 3.12

Figure 3.12 Typical closed welding head set (Polysoude)

The construction of aclosed welding head type is shown in Figure 3.13. The rotation movement of the electrode holder is made by a group of small, together connected gears supporting the truncated circle holder of electrode from at least four points around the holder.

Figure 3.13 Closed welding head type MW 40 (Polysoude)

Open (arc) welding head consists of drive housing, clamping device, driving unit and base plate. Open welding head is shown in Figure 3.14. Open welding head will be fixed by a shell or chuck clamping device around the pipe, and locked at the right place. The welding torch can be equipped with transversal oscillation devices for wider weld and radial movement for adjusting the arc. The head is equipped with a wire feeding system for filler wire, welding gas hose, electric cable and sometimes with water or gas cooling.

Figure 3.14 Open welding head (Arc Machines Inc)

Welding track or bug has a different fixing system. It has a rail or ring, which is fixed around the cylindrical piece and the track itself will travel along this rail. The adjusting of it must be also very exactly perpendicular to the piece too. These tracks may have for instance pipe size from 168 mm to unlimited. The only main limitation is the length of cables and hoses. Welding track is shown in Figure 3.15.

Figure 3.15 Welding track with MAG-process (H.Salkinoja)

Welding track may be equipped with a special narrow gap-welding torch, which is shown in Figure 3.16.

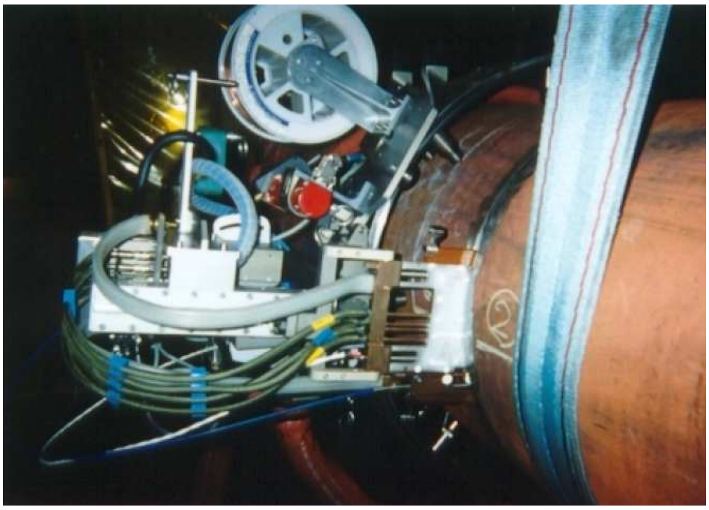


Figure 3.16 Narrow gap welding of thick wall pipe with special narrow gap welding torch (Meuronen/Polysoude)

The last main type of welding heads is shown in Figure 3.17 and it is a special welding head for tubes on tubular sheets. This type is developed for tubular heat exchanger manufacturers. This will be centred with a centring mandrel adapted to the internal diameter of heat exchanger tube and will weld the edge of the tube to the edge of the tube sheet.

Figure 3.17 Tube to tube-sheet welding head (ESAB)

Modern welding power sources and the intelligence of them

Welding power source must be programmable for each individual application and weld. Power sources have programmable welding current, voltage, flow of shielding gas, welding speed and wire feed rate. These are the minimum programmable properties of all models. For thicker materials there is a need for more, and then there is oscillation for wider welds and following of the length of the arc (AVC, Automatic Voltage Control). The most modern models can have some external axes.

The power source can have a real time data acquisition system with adjustable limits of some parameters. For instance welding current, arc voltage, torch travel speed, wire feed rate and hot wire current can be adjusted with active and passive limits. If the value goes over the active limit for longer than 20 ms, the system will stop the process. From the passive area there comes a warning only. There is an example of these limits in Figure 3.18. Welding parameters can be printed out from the memory of the power source.

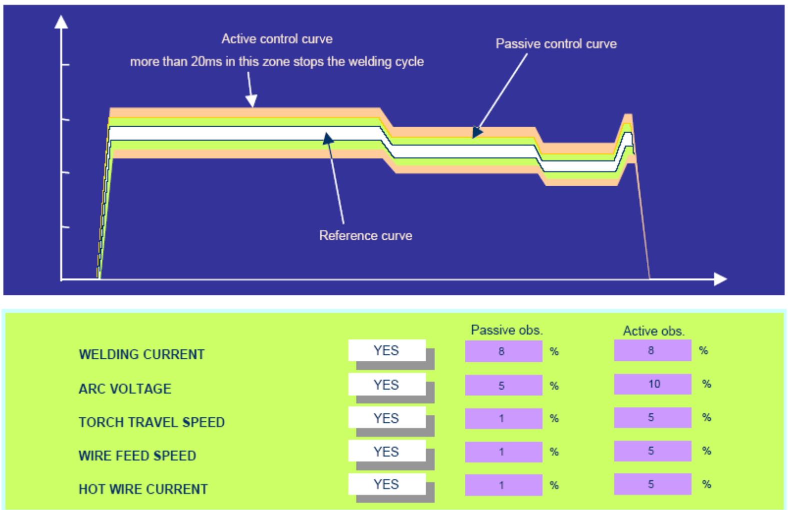


Figure 3.18 Active and passive limits of a real time data acquisition system (Polysoude)

In the power source there is a read alter storage for different programmes and each of these programmes can be stored on a memory stick, memory card or PC too. Some models have their own library for different programmes. As a display terminal for data there may be a LCD-display or external PC. All power sources are equipped with a remote control unit for controlling the process. The operator can adjust some parameters under process to improve the weld. The cooling of this equipment is normally made so that the power source itself has air-cooling but the welding head is cooled by a closed water loop. The weights of power sources vary from some 20 kg (Liburdi) up to 400 kg (Polysoude).

Execution of orbital welding

Joint preparation and system application
Because the system is totally blind for all mismatch in preparation, they may cause deflects in the weld. So orbital welding requires normally very high accuracy for joint preparation. The ends of tubes must be cut with a mechanical saw or lathe to get them really perpendicular. A manual saw or cutting manually steered tools, oxygen cutting etc. is not accurate enough.
In Figure 3.19 there is one pipe saw where the machine head rotates automatically around the pipe and cutting speed depends on the torque and the parameter settings. These machines normally are fixed outside of the pipe and take steering from outside the surface of the pipe

and just cut the pipe perpendicularly and the joint preparation is normally I-type. They are used mainly for thinner wall pipes. For thicker materials there are machines which will be fixed inside of the pipe by a distending mandrel or some jaws. These machines take steering from inside of the pipe and are designed for finishing the end of the pipe for welding. One example of these bevelling machines is shown in Figure 3.20. Inspected from the view of the system intelligence there is a comparison between the quality of the bevel and intelligence level of system and these should always be checked, which is a more economical way to produce the weld.

Figure 3.19 Modern mechanical pipe cutter type (Georg Fischer Piping Systems)

Figure 3.20 American pipe beveller (D.L.Ricci Corp.)

Sometimes there is a need to transport the welding plant closer to the welding place, for instance if the pieces are big and heavy, then the heavy welding system with power sources can be assembled to a movable wagon. This kind of system is shown in Figure 3.21, which presents a movable joining station. The products in this factory are mainly large dairy process equipments where it is needed to weld a lot of tubes in different places around the factory. Pressure levels in the lines are not very high, the material is stainless steel and the material thickness few millimetres so melting with orbital TIG is found to be the best system and it gives good quality for hygiene requirements of food industry. Requirements for investment have been the right quality according to food processing requirements, productivity and reliability. The intelligence of the system is confined to the inside of the power unit and the reprogramming of it. This solution is not a typical solution but proves the company able to innovatively develop its production.

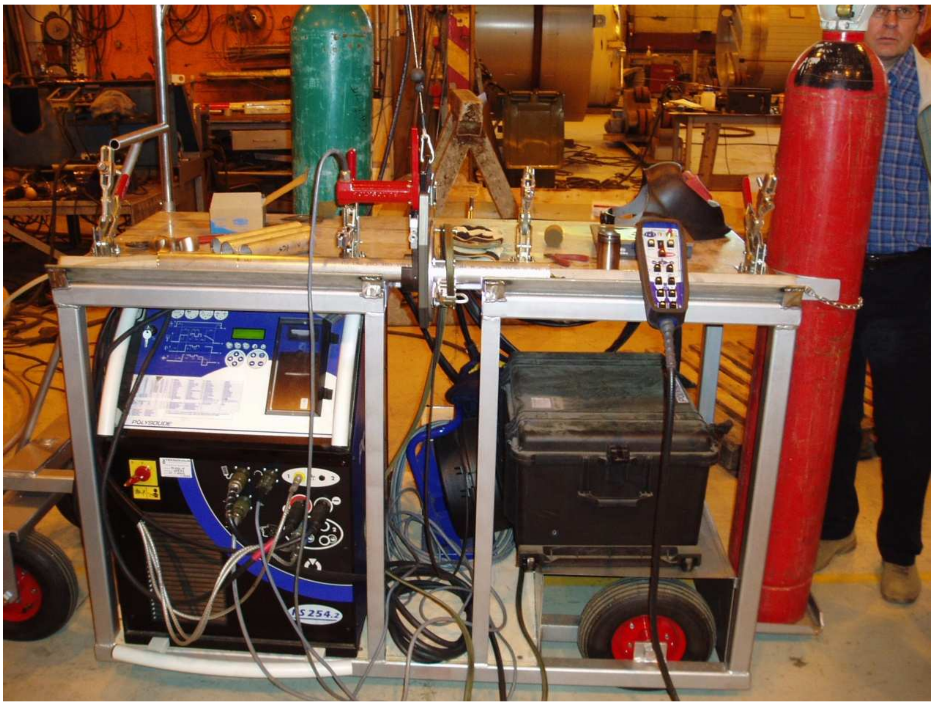


Figure 3.21 Tailor made movable joining station for stainless tubes with open welding head. (H.Salkinoja, courtesy of Tankki Oy)

3.5 Robotized welding

3.5.1 Welding processes and methods

In robotized welding mainly resistance spot welding or metal arc welding processes are used and in some more sophisticated cases laser or hybrid with laser and arc are used. The last versions are remote welding with laser. This is because the filler metal feed is continuous and the welding process is reliable and well-known. Normally robotized welding is used in deadly monotonous welding of similar components and cases which are too complicated for simple mechanizing. The batch size must be big enough to cover delay caused from programming.

In markets standard robotized cells, which can be put in the production line to make some stage or tailor made module solutions exist. More sophisticated systems can have several robots working together, so that one robot is the master and the others are its slaves. The other robot may hold a component and eliminate the need of a jig. A robot can have several tools like torches for welding, cutting, gladding etc. and other tools like steel brushes to clean aluminium before welding.

3.5.2 Practical solutions

The welding of modulated metal made grating fences is a typical example of robotized production cell today. The batch size increased so much that manual welders had no more capacity to weld everything and automated or mechanized system was too complicated or slow. In this case a standard robot with high accuracy piece jig for two pieces was selected. Now the robot can weld one component and the operator can change a new piece on the other side of the jig. When welding is ready, the machine turns a new piece to be welded. The robot does not need any special intelligence. Even seam tracking or finding is not necessary when the pieces and the jig have accuracy that is high enough. The second typical example is welding of aluminium boat hulls which, for every different boat model, need a good fixture for plates, where tack welding is done. Then this system is transported to welding gantry where the robot first cleans welding groove by brushing and then changes the brushing tool to the welding torch and welds the hull.

The more sophisticated system, where an agile robot welding cell is built, is presented in Figure 3.22. Here one robot welds and the second works as a slave for the first one. The second robot can hold and turn the piece under welding and change the next piece when the first one is welded. This system needs more intelligence like rail finding and tracking, camera assisted tool check, tool change systems etc.

Figure 3.22 Welding robot cell in LUT (LUT, Hiltunen)

A robot welding unit may have high level internal intelligence. This makes the system complicated and expensive, because there are several different processes to control. An Intelligentized Welding Flexible Manufacturing Cell (IWFMC) is presented in Figure 3.23. In

Figure 3.23 WP is Welding Power, controlled by its own computer WPPC. SP is Signal Processing Interface for laser scanning, controlled by Seam Tracking Computer TPPC and IP is Image Processing interface which connects vision sensing and intelligent Weld Pool Controller VPPC. 6-freedom manipulator and 3-freedom positioner are controlled by their own MPPC computer. These four computers are controlled by a Central Control Computer CCPC which controls the whole system. This type of a system fulfils the requirements of Level 5 (Tarn & al).

This system needs a simulated model of a piece before it can produce a program for the manipulator and the weld piece. An operator is needed to create a model, load and unload pieces, start a system and supervise if something goes wrong and the system gives an alarm.

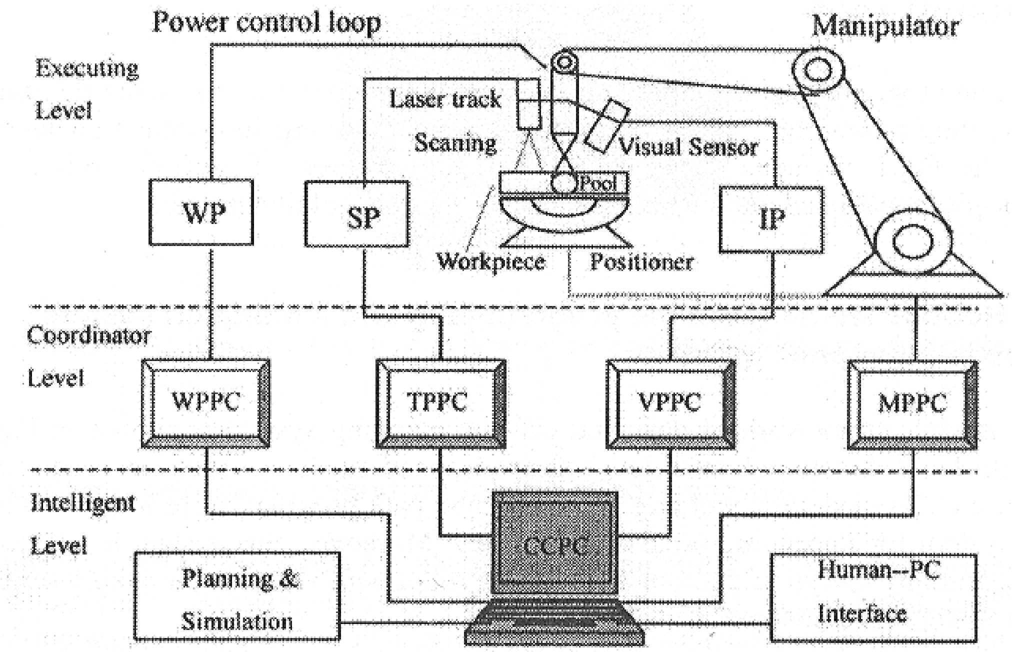


Figure 3.23 System scheme of intelligentized welding flexible manufacturing cell (IWFMC) (Tarn et al. p.125)

Above, there is an example of modernistic welding portals from shipbuilding industry in Finland. This robot welding portal with a vision system which consists of a portal construction a carrying camera and a robot unit is shown in Figure 3.24. The system is made to weld flat components of a hull, like walls or a deck.

First the steel plates and girders of the wall are put on the floor under the portal and tack-welded to the right position. Then the portal will be driven over the component and a camera with a computer scans a picture from the component. The operator will determine the start and end points of the welds in the picture and selects the weld type from the library for the welding system. Then the robot starts to weld automatically following the picture in the computer and with rail tracking it can weld all welds of the component. The system can understand windows, doors and other openings of the component and can piece together the girders and welds of them. This has got the productivity of the welding job of the shipyard to a totally higher level. The principle of this system is shown in Figure 3.25.

Figure 3.24 Robot welding portal with vision robot system (PEMA)

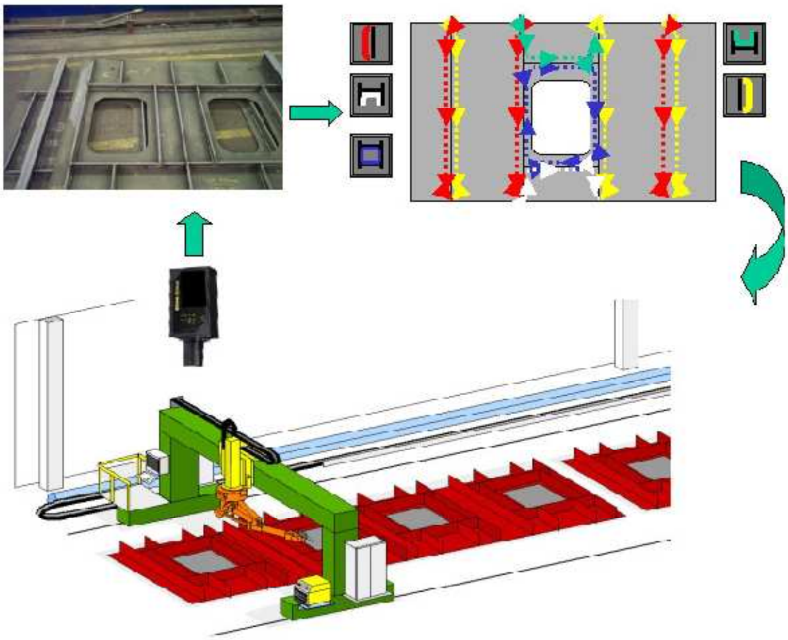


Figure 3.25 Principle of vision robot system (PEMA)

3.6 Adaptive welding

3.6.1 Welding processes and methods

Adaptive welding is used mainly in cases where pre work has difficulties to reach accuracy requirements. This is typical in long welds with big pieces like the welding of big steel sheets or containers. In adaptive welding normally the welding groove dimensions are measured and then the needed amount of the filler wire is calculated and the speed of filler feed is adjusted to get good weld or set bead place in the groove. With these systems it is possible to compensate variations of air gap in square butt preparation when welding big sheets. Welding processes are normally MAG or PAW. Other processes with machine made travel are possible too.

3.6.2 Practical solutions

Jernström has developed in his dissertation a real time quality control system for plasma arc keyhole welding where both welding current and wire feed are controlled on the basis of gap width. Now gap width can be 47 % higher than in welding with constant values (Jernström p. 63). This system has almost a real practical application in one shipyard where big plate sheets for the ship hull are joined together with MAG-laser hybrid process. There is an in-built adaptive measuring system for the weld groove and the system gives warning from too big a gap but does not yet feed more filler wire. Still there is a built in option for the adaptive system.

As the second practical application a system can be mentioned which has a computer vision system with an air cooled camera, and it can measure groove geometry and set positioning and the speed of the filler wire feed adaptively at the right places in the groove. One of these systems can be seen in ESAB factory in Laxå, Sweden. (Lukkari, interview)

There has been one model of the modular welding travel carriage with oscillation and integrated laser guided seam tracking on the market. This model is shown in Figure 3.26 and it can weld both butt and fillet weld with or without oscillation, adapt travel and amplitude of oscillation according to the gap width. It has the movements of the torch in three axis and it seems to present the highest intelligence level of welding mechanization. (BUG-O)

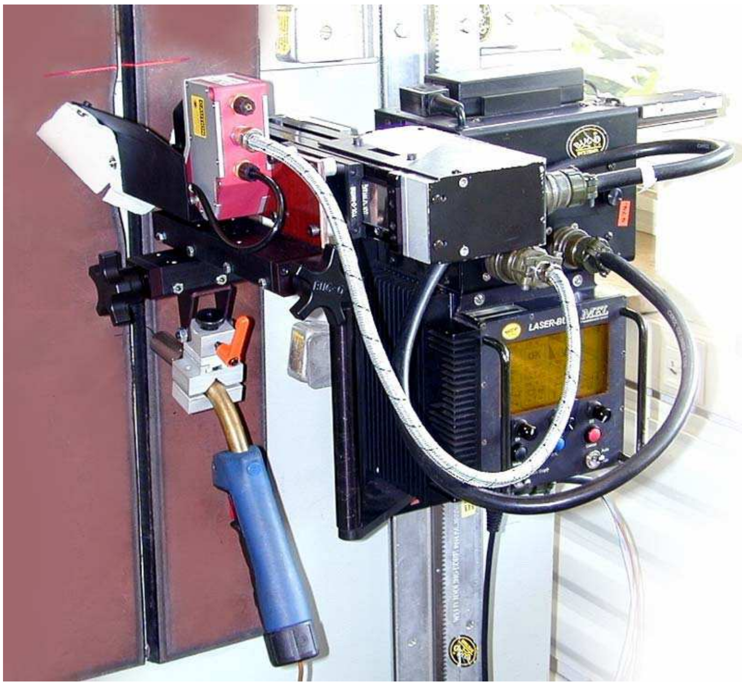


Figure 3.26 Laser guided welding carriage (Bug-O-Systems, MEL Mikroelektronik GmbH)

An external laser guiding system is added in front of the welding torch. First the weld groove will be scanned to the memory of the machine and then the machine starts to weld. It can weld the root pass and 1-4 filling passes and cover the seam layer. It will remember the groove profile dimensions and the location of it according to the covered distance. Also it can adjust the travel speed according to the gap width. The process is MAG.

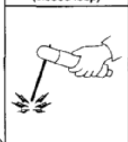
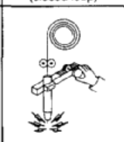
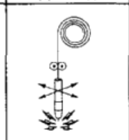
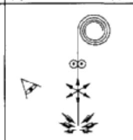
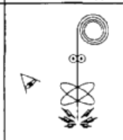
The weld must not be exactly parallel with the quid rail and it must not be exactly straight. The machine has the side movement of 50 mm both sides and there is oscillating of torch too.

4. INTELLIGENCE CLASSIFICATIONS IN WELDING

4.1 Intelligence levels

The intelligence levels of arc welding can be defined in several different ways. Cary has defined these in Table 4.1 where there are different person-machine relationships for arc welding with automation.

Table 4.1 Person-machine relationships for arc welding with automation (Cary, p.290)

Method of Application / Arc Welding Elements/Function	MA Manual (closed loop)	SA Semiautomatic (closed loop)	ME Mechanized (closed loop)	AU Automatic (open loop)	RO Robotic (open or closed loop)	AD Adaptive Control (closed loop)
						
Starts- maintains, and controls the arc	Person	Machine	Machine	Machine	Machine	Machine
Feeds- and directs the electrode into the arc	Person	Machine	Machine	Machine	Machine	Machine
Manipulates- the arc to control the molten metal weld pool	Person	Person	Machine	Machine	Machine (robot) with or without sensor	Machine with sensor
Moves- the arc along joint (travel)	Person	Person	Machine	Machine via prearranged path	Machine (robot) with or without sensor	Machine with sensor
Guides- the arc along joint	Person	Person	Person	Machine via prearranged path	Machine (robot) with or without sensor	Machine with sensor
Corrects- the arc to overcome deviations	Person	Person	Person	Does not correct hence potential weld imperfection	Machine (robot) only with sensor	Machine with sensor

The automatic-adaptive control of the system can adjust welding parameters according to on-line measured process data. Normally the best adaptive control means that a human operator adjusts the system. The modern intelligent adaptive-automatic welding system contains control units with asensor system and can do welding in the right position and reach the correct optimized quality level. Cary has described these components in Figure 4.1.

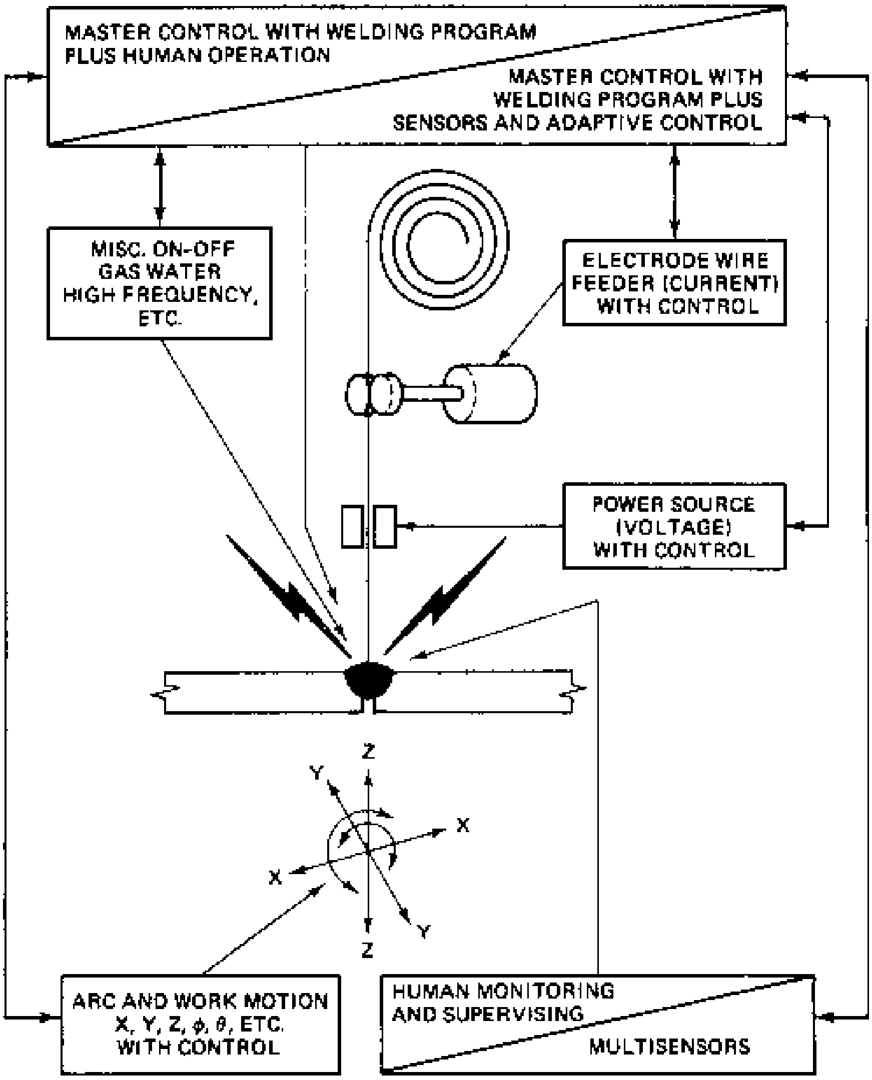


Figure 4.1 Automatic-adaptive control arc welding systems (Cary, p.291)

Pure adaptive control needs no human monitoring or supervising to make weld with proper quality at the right position. Cary has described the principle of the adaptive welding system in Figure 4.2.

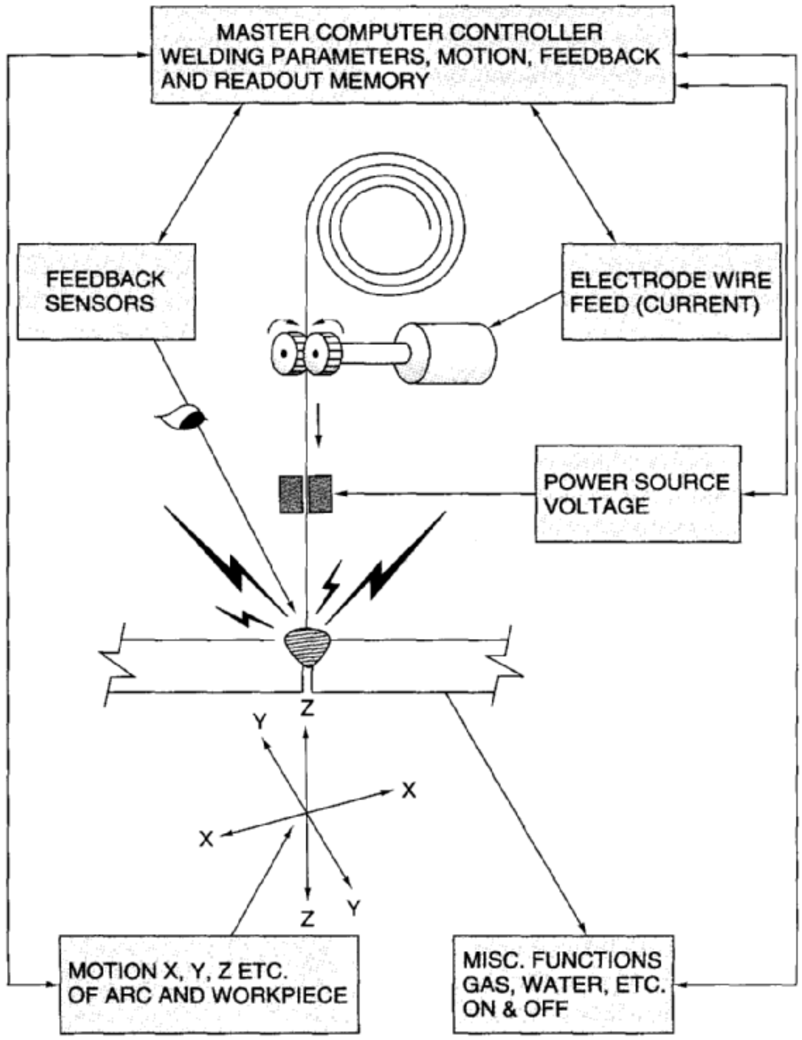


Figure 4.2 Adaptive control of an arc welding syste. (Cary p. 328)

Martikainen has classified the automation levels of welding diner divisions on seven different levels according to the filler feed, mechanization level, customization for one special piece, using robot and different adaptive control levels. This classification is presented in Table 4.2.

Table 4.2 Automation levels of welding (modif. Martikainen)

Designation	Example
1. Manual welding	MMA
2. Semiautomatic welding	Manual MIG/MAG welding (mechanized filler feed)
3. Mechanized welding	Submerged Arc Welding (mechanized filler feed) and torch transport)
4. Automatic welding according to a fixed programme	Customized automate for special piece
5. Automatic welding according to a fixed programme	Robot welding
6. Adaptive welding	Torch control and welding perameters adapt to momentary conditions in joint
7. Optimized adaptive welding	All essential processparameters are measured by system and productivity and quality are optimized by system

Adaptive welding must necessarily have a process monitored by feedback sensors. This can be done by a filtered camera, weld pool size or sound monitoring equipment etc. Seam finding and tracking and pool monitoring are normally made by CCD-camera. (Sharma & al) One experimental system for pulsed GTAW process monitoring is presented in Figure 4.3.

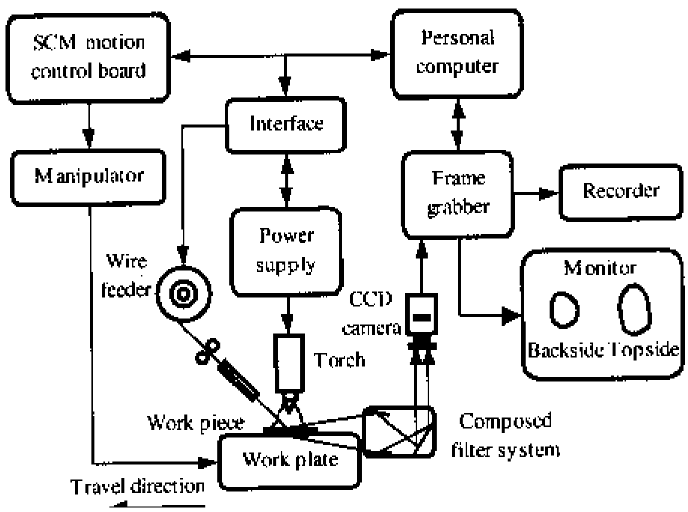


Figure 4.3 Structure diagram of experimental system for pulsed GTAW (Tarn & al. 28)

4.2 Classification of intelligence levels in this thesis

The most difficult professional skills of a welder are manually made welding work, welding torch movement and filling the groove and in this way getting a good weld. A welding system has in-built intelligence and the ability to find the beginning and end of the weld groove, transport the arc well and control the pool with the right amount of filler material.

Earlier classifications made by Cary and Martikainen were based partially on the technical and partially on the functional differences of machines. Cary divides the work made by a person and made by a machine. Martikainen classifies systems according to the automation levels, but does it quite finely in seven levels. It is a little too fine a classification for the internal intelligence of the system if we are building a method for optimizing that level. In this discussion the intelligence of welding is defined as *a systems ability to produce a weld which will fulfil the requirements*. It contains the exact seam finding, seam tracking, arc controlling with the right amount of filler feed and controlling of weld pool to make good weld with exactly the right amount of filler material. Principally these things do not speak out or presuppose anything from technology. These abilities are the most critical things a manual welder must master for example in TIG process. The amount of intelligence levels must be small enough and the classification of all different welding systems must fit in some of these classes. Only in this way it is possible to establish intelligence on basis of productivity, economy and quality requirements.

Intelligence is now classified in the following way in five different levels and in Table 4.3 the typical features of each different intelligence level are presented. (Compare the definition in page 17)

1. ***Manual welding and semi-automatic welding in which the welder undertakes all the operations including tracking the joint, manipulating the welding head (gun or torch) and controls the behaviour of the weld pool to accommodate the variations of the joint.***
2. ***Simple mechanisation in which aids are provided to assist the operator, for example a simple track to traverse the welding head (gun or torch) along the joint but the operator is required to control the behaviour of the weld pool by adjusting the position of the welding head (gun or torch) and speed of travel.***
3. ***Intelligent mechanized system in which aspects of welder skill are included for example, welding head (gun or torch) oscillation to give tolerance to variation in joint gap to facilitate positional welding, but the operator may be required to control the behaviour of the weld pool, for example by adjusting the position of the welding head (gun or torch) and the speed of travel.***
4. ***Pre-programmed automatic welding operation with no requirement for the operator to make adjustments to the welding parameters to control the welding pool.***
5. ***Automatic welding operation with sensors for adaptive control with no requirements for the operator to make adjustments to the welding parameters to control the weld pool.***

Table 4.3 Intelligence levels and typical features of them

Intell. Level	**Typical features of case**	
1	Work made by person. Small amount of welds per year, low productivity. Difficult to automate. On site welding. Cheap investment costs.	Flexible construction types. Difficult accessibility. Low pre work quality. Low deposition rate. No limits for piece size. Not very sensitive to environmental conditions.
2	Person controls the system. Low or moderate investmet. Easy to automate. High deposition rate and productivity.	Geometrically simple weld. Big cylindrical parts. Increasing welding parameters. Profiles, continuing welds. Not very sensitive to environmental conditions.
3	The machine makes weld. Operator must be present. Commonly used in workshop. Quality of weld controlled under welding process. Need of camera assisted followed by operator. Moderate investment .	Big variation of weld groove dimensions for automate or mechanized welding.
4	Unmanned production is possible. Welding fixtures are necessary. High deposition rate, welding parameters and productivity requirements. Monotonous heavy work with high accuracy requirements. High investment costs. Commonly used in workshop.	Multiform welds which may have some modular features. 3-dimensional weld. Moderate or good pre work of parts. Several different products under work at the same time.
5	Unmanned production is possible. Computer vision can give competitive advantages. High productivity requirements. High investment costs. Commonly used in workshop.	Big variation of weld groove dimensions for automate or mechanized welding. Pre work accuracy cannot reach requirements for lower automation. Pieces may be big and heavy. Quality requirements expect adaptive control etc.

4.3 Factors in selecting of intelligence level of welding system investment.

The optimized intelligence level of welding equipment can be defined on the grounds of the following reasons:

1. Weld characteristics
2. Welding process
3. Piece
4. Amount of produced welds
5. Working conditions
6. Quality assurance
7. Seam finding, seam tracking or adaptive requirements
8. Reliability requirements
9. Payback period and cost effectiveness
10. Other things

Each of these reasons must be checked before the optimized intelligence level of welding equipment can be defined. Any of these may give minimum requirement for intelligence or limit the usable level of technique. Especially economical aspect is important, because the system must earn itself. Next, those features are presented closer. The foundations and possible reasons for selecting the welding system and intelligence level of the welding system.

4.3.1 Weld characteristics

The regularity of weld may set *the minimum requirements* for the system intelligence. This means that *at least this level should be selected if old manual welding doesn't seem to be productive enough*. This means how complicated a form weld has.
- Straight weld points can be defined by one coordinate x along the weld. It is easy to mechanize and this gives Level 2 a suitable enough level for this case. This means travel carriages etc. systems are suitable for medium size series and for instance longitudinal tube weld can be made by this product tailored automatic production line with fixed welding parameters. As an example, a longitudinal weld of steel tubes and profiles can be formed from a strip.
- Circle weld can be defined by the centre point, radius and rotating angle. The welds of tubes and pipes are typical applications where Level 2 is again high enough for this case. Narrow gap welding and for example an orbital welding system may need oscillating and this means easy Level 3 as technically optimized level of intelligence. Now the only weld types are circles.
- Two dimensionally curved weld means that the weld is on one plane but has curved left and right and may have different radius or sharp angles on each direction. All points of it can be defined by two coordinates, x and y. In the simple cases the system may use a flexible rail, assembled on the plate, for example, with magnets and travel carriage for the torch following this rail. More complicated cases and smaller radii of curve a higher level of intelligence or special tailor-made equipment are needed just for this case. So this case needs special application of Level 2 or 3 or if there is a lot of variation even Level 4 which is the high

productivity of simple components in which the robot controls the welding operation. Level 5 requires adaptive control to accommodate different parts, variation in parts or variation during welding for example due to distortion.

- Three dimensional curved weld is really curving in all directions and all of its points can be defined with three dimensional space coordinates x, y and z. The piece has often several corners to be welded. Now the torch may have to turn and twist according to the welding direction. This is normally difficult to mechanize with a simple travel carriage and demands the higher level of intelligence from welding equipment. Level 4, for example a robot with a fixed programme, is technically a good solution for this type of welds. Robot welding is typically used for these cases.

A weld type gives requirements especially for seam tracking. *Butt weld* may be the optimum weld type for thin materials but difficult to find automatically. Mechanical, electrical and magnetic systems have normally great difficulties to get the torch to the right place and this is really important for successful welding. So in this case adaptive, camera-assisted equipment Level 5 may give the only possible solution, if seam tracking is important. If the torch mechanically or in another way can be steered direct according to the seam, a lower level is possible. For example, the closed orbital welding head or high enough accurate robot system without seam tracking, can perhaps be used. A blind travelling carriage has problems in pre setting a guiding rail because of required accuracy, but if a wide pool is possible, like for thick materials with high welding parameters, a carriage type is possible and it can compensate inaccuracies of pre-settings. *Fillet weld* is the easiest case for seam finding and tracking system. For example in welding position PB torch travel carriage can get steering from vertical plate and the intelligence Level 2 is enough. Other types of welds are normally between these two extremes and must be handled separately.
The penetration of a single run weld is important. Normal TIG is the most common way to weld the root pass or thin plate butt weld. If the process has higher power density like PW or LW and the full penetration with good quality is required, higher level intelligence like the real time weld quality monitoring with cameras, ultrasonic, x-ray or other intelligent adaptive systems are optimized.

Welding position has its own influence for the intelligence of welding equipment. Down (PA) and flat (PB) are easy to weld and thus more simple systems and effective parameters can be used. Automatic controlling of weld pool in horizontal welding (PC) or even overhead welding (PD) need much lower parameters and more controlled conditions. Welding positions PA and PB have no remarkable effect for the intelligence level of welding equipment if maximum available performance in the world class is not necessary. Level 2 or 3 with carefully selected welding parameters give relatively good performance with much lower costs. On the other hand more difficult positions like PD, PE, PF and PG need a much more sophisticated system like Level 5 to be able to control the pool. In these cases the arc processes with filler feed are often the best welded by highly skilled manual welders. The reason for this is simply that today there does not exist a commercial method or system which could make this work better than a manual welder with Level 1.

The size of the weld may cause its own requirements because a single run weld is not so challenging for automation than multi-run weld. The multi-run weld may need sealing pass with a totally different process or at least different process parameters than filling passes. As a typical example can be mentioned a pressure vessel welding with TIG in sealing pass and MAG or MMA for filling passes because of quality requirements. If the whole weld is made with automatic or semi-automatic welding like mechanized MAG, torch positioning for each pass can be made manually and transport with a travelling carriage. The needed intelligence level remains on Level 2. Of course more intelligent systems can be used, but the necessity of them may be debatable. As an example narrow gap welding can utilize a camera assisted system in controlling the torch position automatically or just show the situation of the arc in the groove for the operator.

The size of weld may correlate with the pool size in cases where high deposition rate is important and normally material thickness is higher. Now welding energy is high and working temperature of the torch is increasing. The torch may be water cooled and the weight of it increases and controlling it becomes more difficult and needs some support for travelling. The so-called cold hand is a necessity to get the productivity high enough. Automatic travelling like carriages and automatic lines of Level 2 or smarter systems of Level 3 are now the most suitable systems.

The quality requirements of weld may require their own intelligence level of welding process and equipment. Pressure vessels have the requirements of good quality and because of difficulties in automatic welding of the root pass there is normally a manual TIG-process for the root pass and some more effective, perhaps mechanized process that is used for filling passes. On the other hand using EB can make excellent quality with intelligence Level 2 or higher, but with higher investment costs, too. Here the decision about the selection of the intelligence level of automation depends much on the comparison between the traditional reliability of manual welding and the reliability of new technology.

4.3.2 Welding process

A product may require the use of a special welding process which needs or actually already contains a certain intelligence level as an in-build feature. Typically a customer or designers have determined the welding process and the manufacturer must use that. In drawings there is often MMA (111) or MAG (136) as the defined process. This defines normally the intelligence level of welding system and unfortunately it is often manual welding. The welding process defines the often used intelligence level, both the upper and lower level of it. Manual welding is on Level 1 and most commonly used. The productivity requirements force a manufacturer to develop their welding systems and use more effective welding machines and processes. Arc processes can be made more effective by increasing the deposition rate, duty cycle, travelling speeds and the use of piece handling systems, travelling carriages, robots and so on. The increasing of the intelligence level may decrease the amount of needed staff and keep labour costs moderate.

Beam-like processes LB, EB and PW need minimum intelligence Level 2, if the system makes similar standard weld under standardized conditions and standardized product like EB welded standardized aneroid capsule for meteorological balloons. If product types may vary but still they have similar features, optimized level depends on pre work accuracy. Now Level 2 may be the minimum level that is acceptable but if the pre work of the bevel is not good enough, there is need to measure the bevel size and calculate the weld volume and adaptively adjust the filler feed which means Level 5 like Jernström has done for the plasma process in his dissertation. In DOCKLASER-project is developed a mobile system for the laser welding of the massive metal plates used to build and repair ships. This will allow greatly increased productivity, efficiency and higher quality compared with traditional arc welding techniques**.** (DOCKLASER)

A product may require a certain intelligence level for welding equipment. As an example we can say small standard pieces with similar welds where Level 2 is enough. Level 3 should be used to give greater tolerance to the welding process, for example, to accommodate variations in the joint. As another example, a small series of different steel constructions like the frame of a special mining vehicle or forest harvester. In these cases the same welding system and equipment are used in the production of several different types of vehicles. Now several types of products are welded with one system. The typical solution of intelligence level is then Level 4, a robot welding with seam finding and tracking systems but according to a fixed programme. Now products have some different types, each of them have their own different sizes or type of welding fixtures, the volumes of welding work are big enough and quality requirements are tight enough so that manual welders with Level 1 are not competitive any more. A robot has a fixed programme where is given a loop to select the frame type for each product so, that in each frame is a number of that type and the robot selects sub programme according to this. Then the robot must have enough intelligence to handle inaccuracies of each individual piece made by pre-work or caused by thermal distortions.

If a company wants to increase the deposition rate of welding, it can be done most easily by more effective welding parameters, manipulators and other systems like these. Using manipulators, travelling carriages, robots etc. normally increase the intelligence level of the system. Manual welding work is monotonous and heavy work. Now torch travelling is done with the so called “cold hand” because of the heat coming from the process, heavy torch with cables and perhaps using tandem or hybrid welding where actually two or more welding processes are welding in the same pool. This process needs at least a mechanized or automated system to control all movements and parameters. If the welds are in three dimensions like the frames of vehicles, then the robot of Level 4 is the most suitable. The upper limit for the intelligence level comes normally from the economical or reliability side like investment and pay-back time. Natural gas pipe welding is here as an example from the view of developing of intelligence in welding equipment. It can be observed that the developing of welding processes and equipment is going to the higher intelligence level. Earlier it was done totally with an MMA-process and nowadays with mechanization like torch carriages and even laser is becoming more commonly used. This system belongs to Level 3. (Vietz)

4.3.3 Piece

If a product requires some special process it often defines the minimum level of intelligence, too. As one example of this which can be mentioned, is the remote laser welding of car body components. Now the product is thin, the form is pressed plate and the requirements for welding are high speed, reliability in strength, smaller width of the welded area (material saving in the lip of the door) and less thermal deformations even with continuous welds which on the other hand significantly improve, for example, the torsion rigidity of the car body. System can be built by a robot with a scanner unit and good fixtures for pieces. Intelligence is on Level 4 and welding time is only a small part compared to resistance spot welding made by a robot.

The pre-work of piece has its own effect on selecting the intelligence level of the system. Accurately machined parts are required for an arc welding robot (Level 4) otherwise the operator can accommodate variation in parts using Level 2 or Level 3 equipment. In the other case, intelligence Level 5, adaptive welding will be the more expensive investment and the manual welding of intelligence Level 1 the cheaper investment. The most economical solution must be calculated closer case by case.

The size of a piece has its own influence for the process and the intelligence level used. Small parts, like tubing, can be welded with Level 2 equipment but equally large structures for example, ship modules, can be welded with Level 2 or Level 3 equipment. Intelligence Level 2 is enough for similar, standardized products which are easy to handle and move like in the circular welding system which is closing cylindrical pieces. (Laserplus Oy)

A piece can be too big or may, in another way be difficult or impossible to handle with welding manipulators. In this case welding system has two possibilities: manual welding Level 1 or very smart system Level 5 like Autonomous Manufacture of Large Steel Fabrications (NOMAD) project where with a simulated system a remote controlled self-moving robot unit finds the piece and welds it according to a designed 3-D model of the piece. This working principle is shown in Figure 4.4.

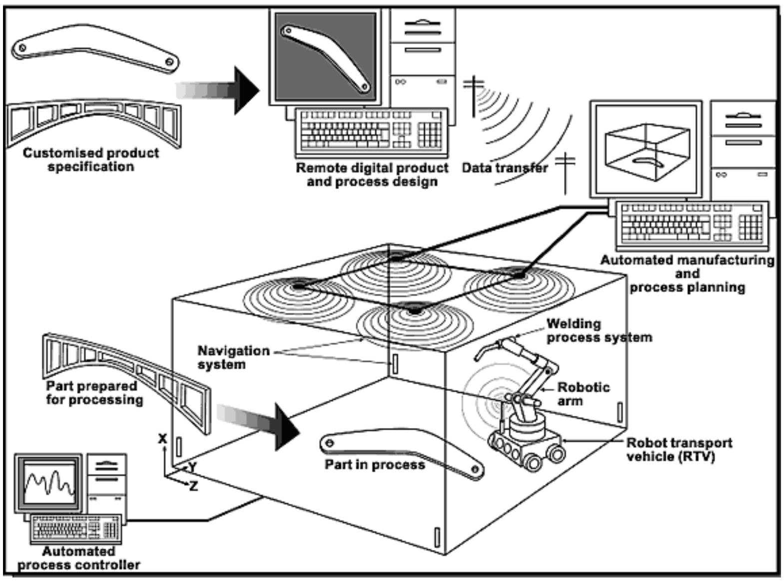


Figure 4.4 Schematic of concept Autonomous Manufacture of Large Steel Fabrications (NOMAD) where with simulated model and autonomous movable robot with sensors good flexibility is reached for welding work of different types of products. (Nomadrobot)

The accessibility of the weld gives its own requirements for the intelligence level of the welding system. If the weld is easy to reach and there are not any obstacles around the weld, it is easy to mechanize the system and use systems like robots or travelling carriages and the intelligence level can be defined on other basis. A good example of this is the plate sheet welding lines used in workshops. The intelligence level may vary from 1 to 5 depending on the needed capacity, plate dimensions and pre-work accuracy. Small plates can be welded manually, bigger ones with automatic fixture for plate edges and travelling unit for the torch and adaptive system measuring the volume of the weld groove and adjust the filler feed according to it.

One requirement for the robot welding is that a robot can reach the weld and there is enough room for a torch to work. The construction of the piece and welding fixtures should not limit the movements of the robot. Then the optimal intelligence level may be Level 4. That is enough to reach productivity high enough and fulfil quality requirements. So, the product must be simple enough

Beam processes LB and EB have exceptional outreach because of their special character. There are some special cases which can be welded only with these systems and then the intelligence level is defined by this reason. Remote laser welding applications and EB with deep penetration through materials via open area inside of a part to the next weld may demand again Level 3 as an optimum.

Often a piece is so complicated that manual welding is the only possible way to make the work with reasonable costs. Such an adaptive machine is yet to be made which will win a professionally skilled manual welder. Manual welding is still the most adaptive method to produce an acceptable quality level weld in difficult places. As an example MMA process with bended electrode and welding with a mirror behind the corner is an excellent example of welding of difficultly accessible welds. The optimum intelligence in practice is Level 1. More difficult accessibility requires a much higher intelligence level or sometimes a special process like diffusion or beam type welding. Mostly, there still, Level 1 is used as the most economical method.

4.3.4 Produced amount of welds

The amount of produced welds has a very important effect for intelligence level optimization. If the amount of normal welds is small, it makes Level 1, manual welding, as the optimum level of intelligence. When there is only one weld which is not very difficult or somehow really special, Level 1 is normally the first choice. But if this weld is of a special type, needs a special process etc. the situation must be checked again.

In the serial production the optimum depends on the amount of similar type welds. If all welds are exactly similar and the amount of them is large, the system can be tailored for these welds only. Now the intelligence level depends mainly on the needed capacity and product type. Mostly there is a simple automatic system of Level 2 or 3 the best, like the flash welding of the chain production. If the amount of welds is one, but it is continuous welding like a longitudinal weld in a tube welding line, an automated welding line, perhaps Level 5 with in-built weld pool monitoring, is the best option. If the welds are almost similar but for instance the welding position may vary or the weld type varies like fillet, butt and lap weld in the same piece the robot welding with intelligence Level 4 is mostly the best from the technical side. The mass production of welded products needs high welding speed or at least a minimized welding time per weldment. The cycle time in welding work of a product must be minimized. Now the optimized system must be fast, reliable and easy to use. This may give the best optimum levels 2 or 3. As Levels 2 and 3 need setting up on each component, they will be slower than a robot which will have the automatic feed of parts. A more simple mechanized system can be faster than a complicated system like a robot or a laser portal. In mass production pre-work has high requirements and prefabricated products must have quality with a high enough accuracy level. The inaccuracies of this can be compensated with the higher level of intelligence (adaptive system) or making the work manually and with much slower speed and higher labour costs.

4.3.5 Working conditions

Working conditions have a strong influence on the optimum level of the intelligence of a welding system. In a workshop a welding system can be closer to laboratory conditions and is easier to build more computerized and use more complicated components, optics etc. higher technology systems than on-site working systems. So there, it is easier to build higher intelligence for the system. On site it is more difficult to bring high technology sensitive systems at the work place, which can be far away from electric networks, roads or be even under water. Environmental conditions, temperature, wind, humidity, radiation etc. may give limits for automation and intelligence level. As an example we can take the repair welding of bottom plate in a coke furnace in a coking works. The temperature of the environment cannot be below 700 C^{o} because the fire proof brick construction of the plant frame will crumble and fall down at once in lower temperatures. The bottom plate of the oven must be repaired by welding. This is done manually with special equipment and outfit. Technically optimum could be Level 5 with adaptive systems but environmental conditions and investment and the development costs of the system are too much for this.

Some cases need that welding must be done automatically because of a dangerous environment like radiation in the welding of tubes under the shutdown in a nuclear power plant. Orbital welding with seam tracking (oscillating with arc length control) is used so that the worker does not have to be close to the piece under arc time. The tubes normally have a thick wall and the weld has several passes. Now the worker needs only a short time to assemble the welding head and can go further off during the welding process. So, intelligence Level 3 is the most suitable in this case.

4.3.6 Quality assurance

If quality assurance is done later after the welding process, it does not have any significant effect on the intelligence level of the welding process. The repair work of welds is very expensive and should be avoided as much as possible. The quality of welding is made and can be improved in three stages, before, under and after welding work. Before includes all pre work, WPS, selection of equipment, process training of welders and so on. The quality assurance made after welding work includes inspections and other quality work made after the welding itself. The intelligence level of welding must be select before and this level system will be used under the welding process. The real time quality assurance of weld can be included in the process for example with process monitoring. Earlier, for instance in orbital welding, a data acquisition system existed (Fig 3.17) and as another example there was a data monitoring system of metal arc welding power sources. A more sophisticated method is on line monitoring of electron beam welding of Ti alloy through acoustic emission. (Sharma & al.) Similar systems but with camera monitoring of laser welding are already commercially available on markets (Precitec). These systems can control the pool and key hole of weld online under welding process. Technically there are only one or few wavelengths followed by the camera either co-axially with a beam or from the side looking assembly. The system will see a disturbance in the welding process and give an alarm, adjust process parameters or for instance mark that place for closer inspection. Now the intelligence level depends on the application and may contain adaptive properties or only the warning announcements of the defect.

Seam tracking is one important area in quality assurance under the welding process. Welding passes must be exactly at the right place. Seam tracking principles may vary from blind mechanical, electro-mechanical to electrically or optically steered systems and the best of them can find the welding groove at the reasonable accuracy from a certain distance. If the welding system contains seam tracking and finding components it has the intelligence level of at least 3. Seam tracking device works together with the torch transport and a worker does not have to control the torch. Often there is a need to visually keep watch so that the process works properly and the weld is made acceptable. The most sophisticated processes may use a camera system and measure the groove size or type and then adaptively control the welding process.

Quality control can be automated and integrated direct after the welding process. This can be arranged for example with eddy current, ultrasonic or for example an x-ray system. Now a warning of a possible defect is received directly after the welding has solidified. The only problem with this and earlier-mentioned on-line systems is, that the repair work must be done later when the piece has cooled and perhaps been transported to another work place. Now repair work causes extra costs and needs time.

If a system could have adaptive process control directly during the welding process and controlling the weld pool there would be savings of costs in finishing the work and improving the quality. This increases the investment costs and maintenance costs but reduces repair and labour costs. Now it will make work more effective and improve productivity. Still we can say, that fully automatic systems (Level 4) are less able than manual welding (Level 1) to accommodate variations in components and also difficult applications.

Quality assurance may define the minimum intelligence level in special cases like difficult welds and under high productivity demands, when manual welding is no more able to compete. The solution and defining of the intelligence level depends now on the total profitability of the investment.

4.3.7 Seam finding, seam tracking or adaptive requirements

Seam finding means that system can typically adjust MAG filler wire or TIG torch electrode at the right position compared with the welding groove when starting the welding work. Normally, this is used in robot welding systems when the tolerance of pre work, piece and robot movements cannot guarantee that robot will find the starting point at needed accuracy. The accuracy magnitude that is required is typically half of the filler wire diameter. Seam finding works so that a robot brings the filler wire contact to the piece surface and with low voltage finds the contact coordinates at that direction and then makes the same in the other direction until there is enough data to calculate a theoretical place for the starting point of welding. This means that the system can go close enough and seam finding just finishes the positioning work. If the robotized system has this type of seam finding it belongs to intelligence Level 4.

Seam tracking means that the welding torch follows automatically the right line in the welding groove under the welding process and the welding pass will find the right position in the welding groove. The system can work principally with several different methods like mechanical, electrical, optical or a combination of these. Seam tracking can be blind and need supervisor to watch all the time like with gravity welding with intelligence Level 2 or optical light spot in SAW in a column and boom application. More sophisticated seam tracking systems may contain intelligence to piece together the groove profile and adapt the torch at the right position to make the pass right. The system may calculate a different position for the next pass and fill the whole multi-run weld automatically. Then the system can be classified to Level 5 because it has adaptive properties. So seam tracking alone does not determine the intelligence level but the type and properties of it can define the intelligence level. Seam tracking may be included in Level 3 and Level 5 systems.

What must be remembered, however, is the necessity of the seam tracking and finding system. More simple is cheaper. It is often possible to make the system totally without seam tracking or finding at all. On the other hand, some applications need a very sophisticated system. For example a butt weld with I-type joint preparation is difficult for normal seam finding and tracking systems. What must be verified is that for instance robot accuracy may be high enough to place the weld to the right position. In some easier cases it is possible to optimize welding parameters like current, oscillation etc. and get the weld wide enough to close the joint.

Here is a place for economical optimization too. The investment costs of good high intelligence seam tracking are high and the benefit gained from it is always limited. Economical and productivity requirements force to make welding more effective and faster. One way to make this is to use an adaptive controlled system in welding equipment. The adaptive control of welding means that the system can measure some important characters from the welding process, weld groove, just made weld or some other starting values and adjust the process parameters according to this information and so improve the result of the welding work. Now the system may allow for example wider welding groove tolerance and bigger variation of them or even optimize the welding process according to total economy.

4.3.8 Reliability requirements

The reliability and robustness of the system in use are very important factors in investment. Modern welding system components like an open orbital welding head are made to produce a circular weld in relatively good working conditions supposing that working place conditions are proper. In a modern workshop this may be so but on-site and for example in the welding of the superheater tubes of a steam boiler in a workshop, the requirements are more demanding. The experiences of real production have given a conclusion that an open welding head is not a very robust construction in a workshop when welding boiler tubes are located very near each other and when adjusting the welding head, the tubes must be bended off from the working area of the welding head. A closed welding head needs quite a lot of room around the tube but is a little more robust against external disturbances. For this type of work there is magnetic blow causing problems in arc controlling when the earth cable cannot always be in this optimized place. So in this case the reliability in the operation causes at least some extra adjusting operations. (Peiponen)

More automation and the higher intelligence of the system give much higher requirements for the reliability of operation especially in a computerized system. And vice versa, a more simple system works normally more sure and reliably. On a principal level it is easy to define the requirements and properties for a system about all that it should be able to do. It is quite another thing to build welding (or cutting) equipment which really can do this all reliably. When a company is selecting a supplier for a high tech, highly intelligent and perhaps even an adaptive welding system, it must find a suitable company which really is able to build that system.

The optimized intelligence level must be realized and it must also *be possible to achieve*. Dreaming in this stage always costs too much. Building a totally new prototype system is always a risk which may become expensive. This has direct effect on the selection of the best intelligence level. A good example is presented in case 4.

4.3.9 Payback period and cost effectiveness

A system must pay itself back according to a company's policy. It cannot commonly define exactly how long this should take. Commonly we can say that the company has to define an acceptable repayment period for this type of investment. Typically this may be, for example, two years.

Commonly there is used the payback method to calculate how long it takes the incremental net cash flows to recover the initial investment. This method asks how quickly the positive cash-flow from profitable operation covers the capital investment. This method has some weaknesses like it does not take the "time value" of the cash flows into account. Also it will ignore cash flows beyond the payback period and it may lead to adopting investments with a higher inherent risk. There is a risk to the rejection of good, wealth-creating project and it does not provide any measure of overall profitability. Other methods are for example the net present value method where the "time value" of money is taken account and if it gives positive value, it indicates that the project is wealth-creating. From net present value it is possible to calculate the discounted payback method where is taken account the time value of money. (Chadwick p.156…159)

Still there are some special values that need to be considered with a higher intelligence level of the welding system. It is very difficult to calculate image values for robot welding or laser welding used in image advertising. In some cases, like replacements, the repayment period of the investments may be much longer than normal. This must be accepted, because the old ancient system is used until the very end and the new one has to be bought and at the same time the company can start using modern technology which can be used for decades in the future.

4.3.10 Other things

The environmental and economical pressure development in the intelligence of welding is growing more sophisticated and coming cheaper like other computerized systems too. Especially, difficult welding work, which is not possible to do manually, will be done as much as possible with mechanization or automatic machines. The main driving forces of intelligence in welding are development in information technology, quality, reliability and serviceability, standards, integration of products and process and safety and health of workers. Simulation technology is increasing and coming more sophisticated and welding will become more integrated to other systems in factories. Also standardization will help systems to work together with a "plug and play" principle. (America pp. 11-22)

According to Welding Technology Roadmap in the USA, challenges for welding in petrochemicals and energy contain collecting and organizing weld properties and data to support modelling, integration, sensors, integrity and standards. Also modelling is getting better for thermal, metallurgical and mechanical change and is integrated into the product's life cycle. Sensor systems, measuring and process control are beginning to characterize and control the weld quality under the welding process. Old and new welding processes will develop to improve quality, performance, costs, markets and environmental performance. (Energetics Inc p.16)

Energy technology processes like offshore, power plant and nuclear technology give challenges for the intelligence of welding. The materials will develop (lean stainless, ultra high strength etc. steel) and they must be welded. All joints are critical and the reliability of them must be sure. So inspection and risk controlling are important.

The trend in the future is the continuous replacement of mechanical joining with semi-automatic and automatic joining processes and robotics, real time process control using computers and sensors and development of welding technology concurrently with development of new materials such as plastics, composites and new alloys as well as the high quality welding of thinner and smaller (nano) materials, efficient designs to minimize the amount of welding. "Zero defect" or "6-sigma" principles for welds with lifetime reparability are important in the future. (Suthey Holler Associates pp.11-12)

In Schweissen und Schneiden 2005 fair in Essen it was seen that in considering internal intelligence is becoming a routine in welding machines. All remarkable manufacturers of welding machines have their own smart version for welding machines. This is becoming popular in all processes but mostly just MIG/MAG manual processes and programming of robotized welding. The reason for this is that these are the most commonly used ones in welding industry. Intelligence in the welding of thin materials and joining of different metals is rising from the demands of the automotive industry. The welding of big thickness steels and big deposition rates in process and energy industry applications require more intelligence to control the pool and the whole process. The direction is to weld effectively more complicated welds than just straight or circular joints and this requires both mechanical and electronic intelligence of the system. Mechanical intelligence means a smart mechanical construction of welding equipment, so that welding is possible. A good old example from this is presented in Figure 6.6.

The deposition rate is increased for example by adding the amount of filler wires to be melted at the same time in the same pool and this gives requirements for the better control of welding parameters of each wire. This is tandem welding with the separate control of welding parameters of both filler wires and in future this will increase to several wires. This system will be used in welding of thicker materials because this way it is possible to get a big cross section weld ready by one pass.

Unmanned production is already used in many industrial areas and robotized welding makes this possible in welding too. The reliability of the welding process is increasing higher and higher and robots will weld as a 24-hour continuous process. Already now it is possible to use endless filler wire in robot welding.

The availability of higher intelligence systems is limited and their suppliers are rare. When selecting the supplier for an intelligent, automatic welding system the practical experience of the company and their references carry weight in the process. This can be checked from the older customers of the company by asking their experiences. Mostly they tell their own opinion and depending on the type of it, it can be taken into account. The company may have earlier experience or a contract to select or use a certain commercial mark or type of systems.

The reliability and exactness in delivery times are the most important things in business today and really important for a company buying a new welding system. These things should be ensured beforehand. At least, a late charge big enough will rule out daydreamers from suppliers and guarantee that the supplier will book enough resources for a project.

Possible suppliers have an effect for optimizing the intelligence level of a procurable welding system. Normally this way, a maximum available intelligence level for a system can be found, but it must always be remembered that the realistically possible and reliable level of intelligence can really be made to work in practical working conditions. So too much optimism will bring a lot of teething troubles and delay in the beginning of production.

Ergonomic reasons may make a company invest to a higher intelligence level welding system. Worker’s health has a really high value for a company because accidents and sicknesses caused by a work may cost too much for the company.

Actually there are always some surprise and not calculated things coming with a new investment. If we can make some forecast about them or about their risks, it may have a great effect on the selection of the intelligence level of the investment.

5. SELECTING OF INTELLIGENCE LEVEL

Table 5.1 shows the selecting and optimizing process of intelligence level of the welding system. All steps must be checked and taken into account and this table helps the selection process. After reading this table it is easier to fill later in Table 5.2 presented case analysis matrix and it gives a general view from the selecting process.

Table 5.1 Selecting process of intelligence level of welding system

Problem definition	**Give framework for selecting**	**Intelligence level**
1. Weld characteristics	Min level with higher productivity Max technically sensitive level	Min and max level
2. Welding process requirements	Minimum level required by selected process	Min level
3. Work piece	Recommendation based on availability and capability to produce acceptable weld	Requirement or recommendation
4. Amount of produced welds	Requirement of cycle time gives recommendation and minimum level	Min level
5. Working conditions	May set requirements for intelligence level and give recommendation	Recommendation
6. Quality assurance	Weld monitoring etc give minimum level and e.g. customer requirements recommendation	Min/recommend.
7. Seam finding, tracking adaptive control	Can be required, then Level 5 or give min level	Possible 5 or min level
8. Reliability & robustness	Realistic evaluation of these give recommendation for level area	Recommendation
9. Payback period and cost effectiveness	Economy gives realistic maximum for investment	Max level
10. Other things	May sometimes exclude some cases or give the highest possible level	Max/prohibition recommendation

Now it is possible to get a recommendation of minimum and maximum level of intelligence and some other recommendations. This system is based on technical productivity, economical aspects and quality requirements. Exceptional reasons for some special cases are taken into account, too. We can now set conditional statements for the optimum level of system intelligence.

Each definition step will be compared with each intelligence level and each of these cases must now give points from 0 to 3 according to their fitness for this purpose. Points will be given according to the following principles according to manufacturing possibilities, economics, quality and productivity of each intelligence level. This point judging can easily be made by checking all possible intelligence levels and fitness of them according the table 5.1 and giving points for each intelligence level.

- 0 point: The welding system with this intelligence level *does not fit at all* for this case. This product cannot be welded or is not sensible to be welded with the system intelligence level of the one in question.
- 1 point: The welding system with this intelligence level *does not fit well but the work is possible to do*. Limited or low level in filling of productivity, economy or quality requirements.
- 2 points: The welding system with this intelligence level *fits on average level for this case.* Average level of filling of productivity, economical and quality requirements. A system with this intelligence level may even be commonly used in welding of this kind of products.
- 3 points: This intelligence level *fits best for this case*. Best possible filling of productivity, economical and quality requirements.

This system can now be collected to matrix where we can calculate the optimum intelligence level. In this matrix is one column for short comments to explain the point judging. Points from 0 to 3 give enough information for selecting the best intelligence level. A smaller amount of the steps would not be enough and more steps would make the classification too complicated and difficult. This matrix is presented in Table 5.2.

Table 5.2 Case analysis matrix

Case No:	**Title of case**					
Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	**Comment**
1 Weld						
2 Process						
3 Piece						
4 Amount						
5 Conditions						
6 Quality						
7 Seam find						
8 Reliability						
9 Payback						
10 Others						
Sum of points						

When filling this matrix, one must check all problem definitions which are briefly commented.

1. **Weld characteristics**
If only manual welding is possible, we must automatically choose Level 1. Increased productivity requires at least mechanized torch transport and minimum level is then 2. Narrow gap applications require at least Level 2. The low accuracy of pre work with high deposition rate required means Level 3 or higher and sometimes adaptive Level 5 is the only possibility to reach good productivity. If a weld is possible to make with a robot and other things do not exclude, Level 4.

2. **Welding process requirements**
Manual welding gives Level 1 automatically. Typically mechanized processes like SAW require at least Level 2. Beam processes like LB, EB and laser hybrid processes need Level 3 or higher. Resistance welding can be made manually but productivity needs a higher level, like in the car industry, typically Level 4. The process itself requires really seldom Level 5. Also we have to check what types of processes are available.

3. **Piece**
A productive and economical way to weld a piece will be defined by the amount of welds, welding position, plate thickness, size of part, material etc. reasons. Thick steel plate construction favours a big deposition rate and this means mechanized or robot welding levels 2, 3 or 4. Exceptions are fixed constructions like assembling on-site where manual welding is still often the most economical method used. Thin sheet can be welded with robotized resistance welding or laser and level is at least 2 or 3. The main principle is to use mechanization and minimize manual work.

4. **Amount of produced welds**
Productivity and the needed amount of produced welds set the minimum level as this amount is possible to be welded with a limited number of staff. Normally this level is in a medium size workshop at least Level 2. Mass production requires robotized welding of Level 4 or automated system which can have intelligence level as low as 2 for example the longitudinal weld of a tube.

5. **Working conditions**
Difficult working conditions set a limit and recommendation for a selected process and its intelligence level. As an example of difficult conditions underwater welding with typical intelligence Level 1 can be mentioned. Another case is outdoor work on site where MAG does not work because of strong wind and SAW is difficult too. Then MMA with Level 1 is the best solution when calculated according to productivity, economy and quality. Commonly, difficult weather etc. working conditions prevent the usage of sophisticated systems and give a low level recommendation. If the conditions are impossible for human people to work (radiation, poisons etc.), the system must be able to make work automatically and intelligence level must be at least 3 but mostly 4 or 5 like in case 8. Adaptive control use often laser beam or other light to illuminate the welding groove and a camera to scan the groove profile. This system is sensitive to surrounding conditions like sunshine, reflections, smoke etc. which can disturb the system and practically prevent using Level 5.

6. **Quality assurance**
Critical welds, like pressure vessels, need heavy quality assurance process too. Now intelligence level depends on the used quality assurance system and the welding

process. Mass production like splice welds of steam boiler wall tubes must have a short cycle time, automatic X-ray testing directly after the welding and now Level 2 is high enough. The longitudinal weld of a tube–type profiles or big plate sheet lines need on-line quality assurance which means a weld monitoring system of minimum Level 3 or Level 5. Small and short welds with random quality assurance testing do not need higher intelligence than Level 2.

7. **Seam finding, tracking and adaptive control**
   Pre work accuracy compared with work piece size and commonly the exactness of the weld groove dimensions and positions, define the need of seam finding and tracking. The need of them means normally a computerized system with minimum Level 3.

8. **Reliability and robustness**
   Lower intelligence gives better reliability and a more robust system. Working conditions in a workshop allow even Level 5 but on site the maximum level is normally 3. Adaptive control means normally the need of steady working conditions, which are difficult to hold constant. This depends much on point 5 working conditions and the intelligence level must be low enough.

9. **Payback period and cost effectiveness**
   Calculations produce the maximum allowable costs and this defines the maximum possible intelligence level.

10. **Other things**
    For instance company politics or image may define the needed intelligence level. Ergonomic aspects may define the possible intelligence level in some cases.

6. EVALUATION OF THE PROPOSED INTELLIGENCE CLASSIFICATION SCHEME

6.1 Welded components and quality of them – special features of process industry

Typical welded process industry components are straight and bended pipes and tubes, different containers, reactor vessels, heat exchangers, flanges of pipes, tubes, valves etc. and all pressure vessels. Typically they have a cylindrical or spherical shell shape because of strength requirements. There must be supporting constructions, basements and frames to carry the weight of these components and their contents. Also there are steel made building frames and other systems belonging to the factory complex.

If one of those critical components is broken, the system or a part of it will come to an end. In the process industry this may have very expensive consequences. The interruption of production in a process industry may cost several thousands of Euros per minute or even cause a life danger. Welded pressure vessels belong typically to these components. Welds are critical for the function of the system and the failures of welding may have fatal consequences. These are reasons why the quality of welds has become more and more important.

The quality criteria of welds are mainly defined in industrial standards. A designer has selected pressure levels and this way the effective forces and required strength of the construction. The plate thickness and weld size come this way. Now a welder must just make welds according to these criteria, which is not always easy at all. The welds must fulfil both the strength and among other things visual requirements too. Fatigue endurance depends very much on the surface of the weld and the amount of undercut, cracks etc. failures in it. So, critical components have tighter quality criteria compared to a normal steel construction. A customer may give his own criteria for welds or welding process which must be followed. One example of damaged critical process components are IGSCC problems in the stainless steel tubes of nuclear power plants. These were found after ten years of using the plant and all of these have been affected by welding and pre work of welding. (Aaltonen pp.4-10) The quality of a weld is made in three stages, before welding work, during welding work and after welding work.

Before welding work we must select the required quality level, weld class (B, C or D, SFS-EN ISO 5817), and do all other designing work. Also a welding process must be selected according to existing conditions. The edge preparation has its own accuracy requirements and the adjustment of components may need a lot of work for example, if electroslag welding is used. Welding equipment may have its own calibration and adjusting manoeuvres like parameters etc. *During welding work* all welding parameters must hold and executing the work must be done carefully and rapidly. Also the controlling of a weld pool is important to avoid welding defects. *After welding work* there is an inspection of welds. This may be only visual and made by welder or more careful for instance by an ultrasonic or x-ray method.

If the first two steps are not well made, the last ones may cause a lot of extra costs for a project. The selection of the used welding process depends on the reliability requirements of welds, and other technical quality requirements. Also the total price of the made weld is important. This includes labour, material and capital costs. Now we have to remember the usability of the welding equipment in production.

In orbital welding the first requirement is especially for the bevel type made for that process and the accuracy of it, which is different from the bevel made for a manual welder. A machine cannot make acceptable quality if the model of the bevel is not made exactly for that purpose. It is totally inflexible for different bevel models. This is typical for sophisticated automation in the mechanization of welding. More automation needs more accuracy in pre work of welded components. The requirement for the flexibility of production and production control is that both automate, mechanized and manual welder can use the same type of the bevel. Now the bevel must be done according to the used welding method. The bevels are made mostly by someone else but the welder and the information where and how this bevel will be welded is not always clear for everybody. Sometimes this causes extra modification work for bevels later.

The second requirement for productivity is that one operator should use two welding heads at the same time. This has not realized because these machines require the full time control of the operator before the quality of the weld is ensured. There is a constant need for small corrective movements of the torch position during welding etc. The welding parameters are ready in the library of the machine and it will drive blindly according to them.

The third important requirement for welding machines in workshops is that they must be robust enough. Now a common comment about these types of machines is that they work well in a laboratory but not anymore in the workshop. Handling them in workshops is difficult because one must be careful not to break them.

The purchasing of this kind of machine must be done so that workers feel it is necessary and belongs to the progression of the work. Workers must have their own motivation to use this. Shift work causes that the same machines have several operators and their professional skills cannot be equal. An old manual welder has his professional pride and attitude that he can make the work better by welding with his own hands. A new machine must show its competence for factory workers too. All these factors have their own effect as a result of this complicated function. Intelligence itself does not make the system good, if it cannot be utilized efficiently. There are different types of cases and the best solutions for them are presented on the next pages.

6.2 Case 1, Level 1: Manual welding of steam chambers

A typical case where the automation and mechanization of welding have not been possible is the welding of t-joints between a steam chamber and steam tubes. This kind of construction is presented as a layout in Figure 6.1 and the chamber inside in Figure 6.2. Steam tubes have an outer diameter typically of 63.2 mm and the drum may be typically about 300…600 mm. Steam tubes must be welded as close to each other as the structural design allows and it is technically possible. Normally there is no space to weld from the inside and all welding work must be done outside the structure.

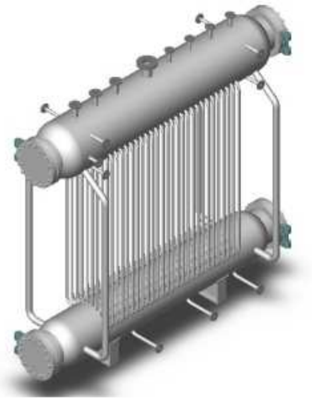


Figure 6.1 Typical construction of a waste heat boiler tubing with steam drums (Envirokinetics)

Figure 6.2 Inside of steam drum of an old ship steam boiler (Flikr)

Analysing of this case gives the following results:

- Weld characteristics are circular or very close of it.
- Best processes which are well-known, totally controlled, highly experienced and give sure results with low process costs, are TIG for root pass and MMA or MAG for filling passes, which means that there may be a need for changing the process under the welding work. Modern processes like LB or EB may have difficulties with international pressure vessel standards.
- A piece is a pressure vessel with a tubular thick wall shell and a t-branch of 90 degrees with standard tube diameters and materials. This may cause a higher working temperature. There is not enough space for any automated MAG-torch and the only possible processes are manual TIG, MIG, MAG and MMA.

- The product amount of exactly similar welds is hundreds and this supports for a fully automated system.
- Working conditions are controlled workshop conditions, so they should not be too difficult for automation.
- Quality requirements are very tight (normally always NDT like penetration colour or ultrasonic testing) and this favours a well-controlled system.
- Adaptive properties can be avoided by a high enough accuracy of pre work in bevelling which is already used because welding bevels are machined.
- Seam finding and tracking is not necessary because the place of each weld already exists in computerized modelling but on the other hand thermal distortions, like the bending of the piece, are big.
- Reliability requirements for a welding system are high but working conditions are not very difficult.
- Payback requirements are on a normal level.
- Suppliers for the welding system must be reliable, experienced and well known.
- Need of well-trained workers.

In this case the welding system must be really complicated, extremely small and flexible to fit in such small places where welding must be done. This mean that costs of automation and reliability requirements for such a complicated system are just too high. Numerical analysis is presented in Table 6.1.

Table 6.1 Analysis results of case 1

Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	3	3	3	3	Easy circle
2 Process	3	3	3	3	3	TIG, MMA, MAG, SAW
3 Piece	3	0	0	0	0	Limited space for torch
4 Amount	1	2	2	3	3	A lot of welds
5 Conditions	2	1	1	1	1	Workshop
6 Quality	3	3	3	3	3	Pressure vessel level
7 Seam find	3	1	2	2	3	Manual or adaptive best
8 Reliability	3	3	2	2	2	Simple best
9 Payback	2	3	2	2	1	Compared to deposition rate
10 Others	3	0	0	0	0	Only manual welding possible
	26	19	18	19	19	Level 1 best

There is not found any economically and productively sensible mechanization which could manage this problem. For instance, friction weld is not possible because of the length of bended tubes and that inside of a hole must be smooth for a steam or water flow. The only possible and reasonable process seems to be MMA or TIG.

Case 1, steam boiler chamber, is technically nearly impossible to automate because there are really high requirements for the weld and the root side of the construction must be good too. The automatic or mechanized system would be too complicated and expensive to reach the needed level of reliability and safety for results made fast enough. There is just no space for mechanization.

6.3 Case 2, Level 1: Repair welding

In this case the problem is normally like repairing of a broken machine component, adding of material to the worn surface or for instance repairing of rust etc. damages of a car body. Typical applications are shown in Figure 6.3 and Figure 6.4. Also underwater repair welding and aircraft landing gear or motor carriage welding are typically manual work even if they are not repairing but still small scale manufacturing.

Figure 6.3 Repaired exhaust manifold (Artsautomotive)

Figure 6.4 Surface repairing of a cement screw (Miningindustrialengineering)

Typical features of these cases are that there is only a minor amount of welding and there is no much regularity or exactly similar welds. Mainly there are only one or a few welds which are of similar type or shape. For example the broken propeller blades of an outboard motor in Figure 6.5 have exactly a similar shape when work is done but a totally different shape when starting the job.

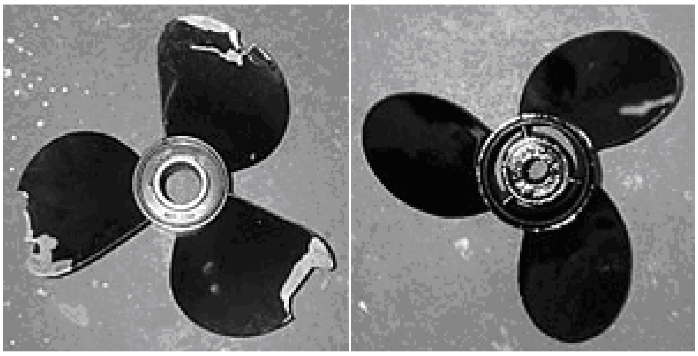


Figure 6.5 Repair welding example of a propeller (Brainerdrops)

In some cases it is possible to mechanize repair welding. As an example when hard facing a cement screw it may be possible to use the rotation of the piece and the mechanized transport of the torch but mostly every case is more or less individual.

Analysing of this case gives the next results:

- Weld characteristics may vary very much and this prefers intelligence Level 1, manual welding.
- The best processes, which are well known, highly experienced and give as sure a result as possible with low process costs are TIG, MMA or MIG/MAG. This allows automation and at least intelligence Level 2.
- Pieces have normally some similar features like crack or wear but they may vary very much between different cases so automation possibilities are small.
- The product amount of exactly similar welds is normally one and this does not support automated system.
- Working conditions may vary from a controlled workshop to on site welding even under water, so it is a restriction for mechanization or automation.
- Quality requirements vary from a very tight, for instance in airplane welding, to low if a system just must be joined and they will not carry any forces.
- Seam finding and tracking is not economically sensible because each weld is normally totally different and building of a tracking system for this is difficult or at least very expensive and adaptive properties cannot normally be used at all.
- Reliability requirements for a welding system are high and standard types of commercial machines are the most economical solution.
- Payback period can be said to be extremely short because repair welding is normally not the main business of a company. This means really low-price machines.

- Other things depend much on the piece and case. Suppliers for a welding system must be reliable and the maintenance of machines must work well and this again prefers simple standard, commercial equipment.

In repair welding there is such a big variation of work pieces that every kind of automation is not profitable as an investment. The amount of series is normally about one and the next work is totally different. If there is regular repair welding of an exactly similar case like resurfacing of tramway rails, then it is naturally easy to mechanize the work for example by using of carriages and the flux-cored wire submerged arc welding process. (Rausch et al.) Numerical analysis of repair welding is presented in Table 6.2.

Table 6.2 Analysis results of case 2

Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	0	1	1	1	Vary very much
2 Process	3	3	3	3	3	TIG, MMA,MAG,MIG…
3 Piece	3	1	1	1	1	Vary very much
4 Amount	3	2	1	1	1	Vary very much
5 Conditions	3	2	2	1	1	Vary very much
6 Quality	3	2	2	2	3	Depending on the case
7 Seam find	3	1	1	1	1	Not normally necessary
8 Reliability	3	1	2	2	3	Must
9 Payback	3	1	1	1	0	As short as possible
10 Others	3	1	0	0	0	Mostly only manual welding
	30	14	14	13	14	practically possible.

The most common cases in repair welding can be handled most economically by manual welding with intelligence Level 1. This can be understood by the working skills of a manual welder, most effective adaptive properties for each individual case that only a human worker can do. Also it means that the process used is normally very cheap like MMA with most wide sorts of different filler materials on the market.

Repair welding has normally so small batch sizes that only manual welding is economically possible. If these cases would be mechanized, the system should be really flexible or then the amount of exactly similar welds must be high enough like some gladding applications.

6.4 Case 3, Level 2: Mechanized welding of nozzles and t-branches in thick wall pressure vessels

One process equipment and heat exchanger manufacturer had a need for a more effective welding method in the welding of t-branch of thick wall pressure vessels. Mainly MMA-process was used in this case. Products are mainly pressure vessels and materials low alloy construction steel or heat resisting, duplex and stainless type steels. Some of them need pre heating up to 300^{o}C. Material thicknesses ranges from 6mm to 100 mm and mainly about from 30 mm to 60 mm. Quality requirements are according to standards tight and the orders of the authorities give their own requirements for work, and the weld must have full penetration.

This is a very typical welding problem where the productivity of welding work is low and the deposition rate of the manual welding process is only about 3 kg/h. The flexibility of the process is excellent and allows the designer freedom to select the bevel type. The earlier design of joint bevels depends on material thicknesses and the diameters of the nozzle branch and shell cylinders. If the nozzle has smaller wall thickness than the shell and the shell diameter is large enough, the cheapest way to the bevelling is turning a narrow J-bevel to the nozzle end and during boring the hole, to plane the shell. The weld is now a flat circle. Then the welding position is PC, horizontal position. Now the cross-sectional area may vary, so that on the crest of the shell there is the smallest area and on the side there may be some not machined shell surfaces and this means more cross-sectional area of the weld. This is difficult to automate because the machine should have adaptive measuring for the weld volume at each section. A manual welder has no problems to fill everything independent of the sectional area.

If the shell has smaller wall thickness than the nozzle, it is better to design the weld so that the nozzle penetrates the shell and make a saddle weld. Now the bevel of the weld is K- or ½V-type and the volume of the weld is minimized. The K-type is taken if there is enough room for a worker to weld inside. The ½V-type bevel is possible to weld in flat position PA. There is a bigger sectional area on the lower sides of the saddle weld, but they are easy to fill both by manual welding and using mechanized welding in manual mode.

Analysing of this case gives the next results:

- Weld characteristics are easy saddle with high volume ½V-bevel.
- The best productivity and deposition rate has SAW process, which means pretty easy automation possibilities but limited welding position. MAG process is possible, too.
- The piece is a pressure vessel with a tubular thick wall shell and a t-branch of 90 degrees with standard tube diameters and materials. Pre heating is often needed.
- Product amount of exactly similar welds is typically two pieces and this support manual welding or simple programming of the system.
- Working conditions are a workshop with high pre-heating, so it is fit for automation.
- Quality requirements are very tight (normally always NDT like X-ray or ultrasonic testing) and this favours a well controlled system.
- Seam finding and tracking are not necessary. Small series cause a lot of programming for a robot. Adaptive control is not necessary.
- Reliability requirements for the welding system are high but working conditions not very difficult.
- Payback requirements are on a normal level.
- Other things like the training of workers should not be a problem. Suppliers for the welding system must be reliable, experienced and well known.

Now it is possible to use mechanization or automation in the welding of these saddle welds. Possibilities are high-tech robots with weld volume measuring or more simple systems, which still have better productivity. There are projects that exist where a robot will first check bevel and the volume of it and then fill it by welding. These systems require for example a portal-type gantry where the robot is hung upside down over the nozzle. The problems of these systems are programming time, set-up time and costs of investment. Still the root must be

welded manually with TIG-process because of quality requirements and the reliability of the process.
Now there are two similar welds per one heat exchanger, incoming and out-going nozzles and the amount of similar exchanger types is on average between 1 and 2. Non-productive time like programming of the robot and the set-up time increase too high compared to the productive welding time. A more simple system is for example shown in Figure 6.6, a mechanized circle welder with SAW-process equipment.

Welding work and a test cut of the bevel in a shell plate is shown more closely in Figure 6.7. Bevelling must be done with higher accuracy than what manually can be reached. This means mechanical machining or some mechanized cutting like flame, plasma, water jet or laser.

In this case cutting is done with a mechanized flame cutting machine that can use both flame and plasma cutting equipment and is designed to cut saddle bevels. In any case the root pass must still be welded manually.

In this case the need for improving of welding efficiency came from ergonomics of work and from markets. There is always a clear need to get higher productivity and more efficient fabrication. In both cases, manual and mechanized welding need manually made sealing run usually with TIG. Filling runs can be made both manually or mechanized. The better deposition rate of SAW make it faster compared to MMA only if the volume of each individual weld is big enough and the amount of welds per year is big enough too.

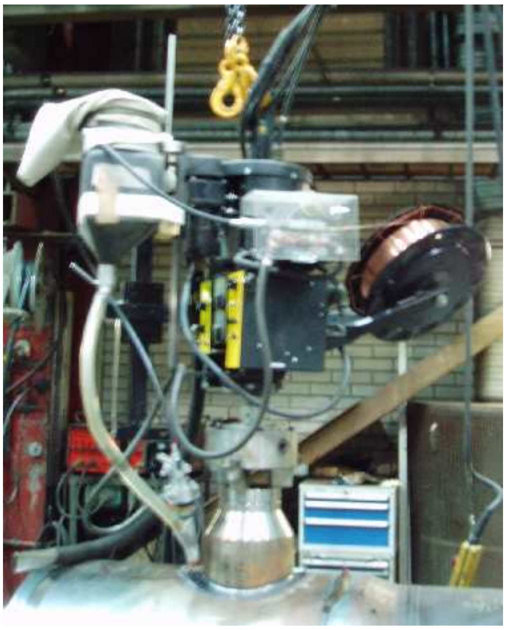


Figure 6.6 Circle welder with SAW-equipment in production in case 3 (H.Salkinoja)

Figure 6.7 Welding of branch with mechanized SAW and mechanized flame cut bevel (H.Salkinoja)

During comparison between welding times it must be remembered that the set-up of mechanized welder takes approximately some 15 min and the take-off takes some 5 min and manual welding is here faster. Totally it is approximated that preparation work has a similar cost level. This means, that the machine must earn itself only by the faster welding time and bigger deposition rate. Numerical analysis of case 3 is presented in Table 6.3.

Table 6.3 Analysis of case 3

Problem definition	**Intelligence level** 1	2	3	4	5	Comment
1 Weld	2	3	2	2	3	Saddle weld, big volume of metal
2 Process	1	3	3	3	3	Big deposition rate needed
3 Piece	3	3	3	2	2	May have high working temperature
4 Amount	3	3	2	2	2	Small series, big metal volume
5 Conditions	2	3	2	3	3	High pre-heating temperature
6 Quality	3	3	3	3	3	Pressure vessel
7 Seam find	3	3	3	2	3	Robot needs a lot of programming
8 Reliability	3	3	2	2	1	As high as possible
9 Payback	1	2	1	0	0	As high as possible
10 Others	2	3	2	0	0	Simple better
	23	29	23	19	20	Level 2 best

If we calculate Ø168 mm nozzle weld volume with typical 50 mm shell thickness and ½V-bevel of 37 degrees angle of bevel and extra filling to 45 degree fillet and 6 mm TIG sealing run, we get sectional area of 1639 mm^2 and the volume of weld 994457 mm^3 calculated along the centre of gravity of the weld cross section, which is about 7.8 kg by density of 0.00785 kg/mm^3. Compared to the measured welding times in workshop floor with MMA-method and J-bevel, this work would mechanized come more than one hour faster. For the bigger diameters of the nozzle and bigger material thickness the saving of time is much bigger, even tens of hours. Now the profitability of the investment depends only on the amounts and types of the welded product per year which depends on markets etc.

The company decided to buy a mechanizing system which is shown in Figure 6.6 and which is fit for nozzles diameters from 168 mm to 600 mm. The payback period was calculated to be about 2-3 years only in welding thick wall nozzles. Any other possible pieces and possibilities to weld them were not calculated. These were for example a manhole of a container and other possible products. Productivity has increased because of the higher deposition rate and because bevelling can be done faster and with higher accuracy by oxy-acetylene cutting. For this purpose the company invested in a similar circle burner as used in tests.

The new process had natural problems in the beginning, but after the start-up and learning it has been a useful system. Productivity has increased just in those areas and products were forecast. The amount of productivity was increasing, but depends a lot on the types of welds, plate thicknesses etc. Sometimes a thinner wall t-branch assembled through a thick wall shell need manually made about the same weld volume in the root of the ½V-bevel than the whole joint made manually direct on a flat planed thick wall surface. The reliability of the mechanized welding machine has been good, but the worker must remember the limits and other properties of the machine. This type of machine must be light and simple enough, movable and that means it is delicate too. The quality of welds has been on an acceptable standardized level and weld repairing work caused by a machine is not needed. On the whole it can be said that intelligence Level 2 was at the optimum area.

6.5 Case 4, Level 2: Production of shower pipes and pulp discharge pipes

Shower pipes used in paper pulp processing are pipes made from stainless steel, their diameters are from 28 to about 60 mm and length varies but is normally a few meters. The pipes are mainly straight and they have one or two row threaded sleeves for nozzles and position. The amount and distance of them vary between different pipes. The average amount of sleeves of one pipe is about 50. So pipes are not exactly similar with each other. These pipes are made by a subcontractor which is specialized in pipe welding. Typical products are these shower pipes, pulp discharge pipes and other complicated pipe products mainly for pulp and paper industry containing a lot of welding.

In existing production principle is to cut a pipe to a given length, end finishing, cut holes by drilling or plasma cutting and manual welding of sleeves and possible supporting components and connecting flanges etc with TIG process. In the production turn tables are used to facilitate the work.

One extra problem is that even though the thread of sleeves is standard, small female pipe thread ¼”, the outer diameter of sleeve may vary from some 17 mm to 20 mm between different batches bought. This means that always before making the holes for sleeve welding, the diameter of sleeve bodies must be measured and the diameter of holes adjusted according to that.

Other products of a company contain pipe diameter area of 80-250 mm and a few times a year even wider. Other typical products are the cross components of pipes which may have flanges too and pulp discharge pipes. Here may be a saddle cut and weld or then the hole is formed from the pipe as a flange, so that the weld is a flat circle. The company needs plate cutting for the plate size 3000 mm x 1500 mm too. This could be connected to a system if it does not cost too much.

Analysing of this case gives the following results:

- Weld characteristics is easy saddle or flat circle if the hole in the tube is formed as a flange. Weld diameters vary normally from 14 mm to 42.4 mm and the weld type is butt weld or fillet weld. Material thickness is few millimetres and the welding position mainly PB or PC and with such a small weld the weld pool is small too and positions are not problems. When it comes to weld characteristics the minimum level would be Level 2.
- The best process which is well known, totally controlled, highly experienced and give sure results is TIG, MAG, PAW or LB, because the weld size is small. This means pretty easy automation possibilities without technical limits and all levels of intelligence fit.
- The piece is a t-branch of 90 degrees with different pipe diameters and the accessibility of weld is not a big problem for a normal rotating torch. Laser may need a special type of welding head. From this side there are no limits for intelligence levels.
- The product amount of exactly similar welds is several tens or hundreds per batch and this supports automation welding or at least mechanization of Level 2.
- Working conditions are a well controlled workshop, so it should not be too difficult for fine and sophisticated automation.
- Quality requirements are normal (normally only visual testing). But some welds need full penetration because the inside must be smooth.
- The problem was sleeve diameter variation, which needs adaptive properties but this can be avoided by selecting sleeves according to the outer diameter before drilling holes and making holes according to each batch of sleeves. Seam finding and tracking is not absolutely necessary but may help the process a lot.
- Reliability requirements for welding system are high but working conditions in a workshop are not very difficult.
- Payback requirements are on a normal level. This means that productivity must be bigger than with manual welding and this means that minimum Level 2, mechanized welding was suitable. So, at least low cost mechanization should be selected.
- Other things, like the training of workers, should not be a problem but must be taken into consideration in the calculations. Suppliers for a welding system must be reliable, experienced and well known because of a big economical risk for a small company. This favour more for simpler than complicated systems.

A company decided to search for the laser welding possibilities of products. There was an obvious possibility to cut holes and plates with the same system. This needs automatically the intelligence level requirement of Level 5, adaptive system because of diameter variation of sleeves.

One supplier made an offer for a combined laser cutting and welding system which consisted of a portal system with a plate cutting table and pipe handling system which would automatically measure sleeve diameters, cut holes with these diameters to the given locations for pipes, cut a pipe to a given length and have a normal plate cutting table combined with the system too. This very promising system would be able to solve nearly all production problems at once and for all. The intelligence level of this system was Level 5, adaptive system.

If we think about this case, productivity would increase dramatically and the quality of laser welds would be excellent compared with old manual welding. Still the economical aspect was not yet sure.
The risks of this investment were that this innovative system was actually a totally new prototype which surely would have its teething problems. The laser resonator itself is already a standard product. A question without an exact answer was how long a start up it needs and when exactly it would be in full production. The second risk was a really high price of the investment compared to other possible solutions with different intelligence levels and more ability of it to pay itself back fast enough.

Now the company started to look for other possibilities to improve the welding and manufacturing of shower pipes. The plasma cutting machine was already very old and should be replaced with a new system. So there were possibilities to purchase a laser, plasma or water jet cutting system and continue welding with manual or partially mechanized TIG process.

At the end of analysing the economically best solution, was to buy a water jet cutting system. This is slower than laser but it is really reliable, fit for all (even non metallic) materials, steering possibilities are good, technology is proven and both investment and using price only fractional compared to laser. Situation was similar compared to a pure laser cutting system which was offered abroad. Also a similar jet cutting system was already working in another company in eastern Finland, where it could be looked at and could be used as reference.

Final calculations gave a result, that the cutting capacity and speed of the water jet was big enough. At the end company invested to the water jet cutting system and continued with a manual TIG process, partially mechanizing and orbital welding. It must be mentioned that in the welding of pipe fitting a manual welder with a turning table was faster than an orbital welding machine. A pulp discharge pipe contains several ten t-joints very close to each other and here it was measured that a manual welder is faster than mechanized orbital welding.

Shower pipe welding is very challenging work for an automated system. Evaluated method proposed an adaptive system. Production data should be taken directly from electronic files and cutting of pipes and holes, measuring, adjusting and welding of threaded sleeves would be done automatically. It is possible to do it with modern technology, but the risks of failures, delay of the start up of the production etc. risks and high investment costs caused that intelligence *Level 2* in cutting and welding would be the best in this case. The company decided to invest water jet cutting of tubes and get plate cutting with an easy option with the machine and welding machine will be mechanized welding with intelligence Level 2. To solve this problem a numerical analysis of this case is made, which is presented in Table 6.4.
Now there was still a problem of how to improve the productivity in welding of nozzles and sleeves. The welding of sleeves can be mechanized for example with a machine like shown in Figure 6.8 and Figure 6.9. These types of machines are available on free markets and they are standard machines and they can be classified to so-called low cost mechanization with intelligence *Level 2* which is recommendable because the machines have a budget price compared to any more sophisticated systems with a higher intelligence level. The only

problem of these machines is, whether the working diameter area is fit for the products of the company. For instance according to brochures of manufacturers, this circle welder in Figure 6.8 has a working area up from 25 mm and the other one in Figure 6.9 up from 20 mm which are too much for the needed 14 mm in this case. A domestic manufacturer of the machine in Figure 6.9 promised that a smaller diameter is possible to weld and under writing this dissertation the company decided to continue with testing this machine.

Table 6.4 Analysis of case 4

Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	3	3	3	3	Easy cicle, fillett weld
2 Process	3	3	3	3	3	MAG
3 Piece	2	3	3	3	3	Pipe, max 6 m, not heavy
4 Amount	1	3	3	3	3	Mass production of welds
5 Conditions	3	3	3	3	3	Workshop
6 Quality	3	3	3	3	3	All levels can reach
7 Seam find	3	3	2	3	3	Adaptive not necessary
8 Reliability	3	3	2	2	2	Must be high
9 Payback	1	3	1	1	1	As short as possible
10 Others	1	3	3	3	3	Ergonomy
	23	30	26	27	27	Level 2 best

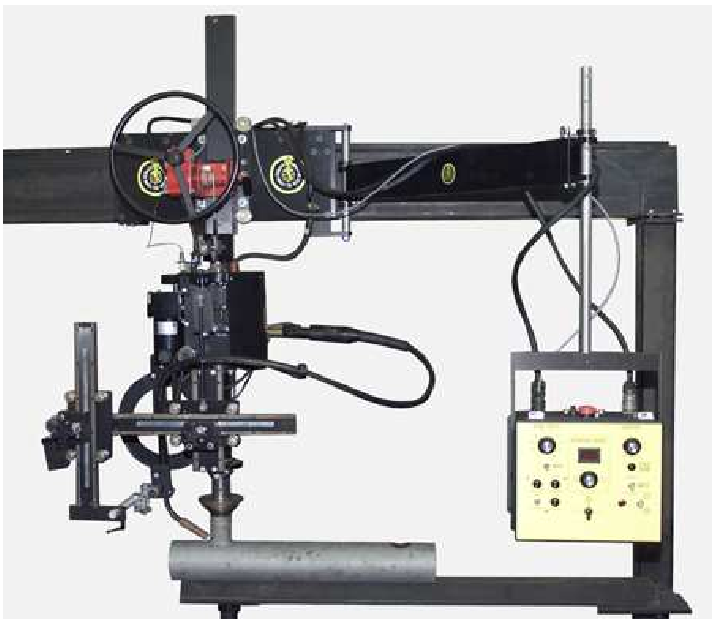


Figure 6.8 American circle welder for small sleeves. (Cypress Welding Equipment Ltd)

Figure 6.9 Finnish made nozzle welder (Kemec)

The production of shower pipes was possible to make with the full adaptive measuring of nozzle diameters and make holes to fit just these nozzles and weld them automatically with laser. The investment was just too high compared to the production size and because the system was the first tailor made prototype for that case, the risk could have been too high for a small company. The system must be as simple as possible and robust enough to work 24 hours per day. A raw tube is now drilled with the water jet and nozzles will be welded in separate stages. The reliability of welding is ensured by using famous and experienced, domestic manufacturers, so the maintenance is sure too. When looking for safety in work, it can be noticed that the system is comfortable for the user compared to any manual welding machines. The operator is not loaded by static forces like handling of the torch etc. or direct radiation from the arc. The system is steered from a steering panel and smoke and fumes are sucked directly off from the arc. Now intelligence Level 2 was the closest to the correct solution. Also we have to notice that Levels 4 and 5 have got a good result and if there are some problems with the quality of welds etc. in testing the mechanized welding, it is possible to select one of these levels, because the analysis gives low points in quality for this case.

6.6 Case 5, Level 3: Production of big plate sheets in a shipyard

Earlier Aker Yards, now STX Europe has in its Turku yards, in production, a laser-MAG-hybrid welding line for big plate sheet joining. Those sheets are needed for ship hull constructions. Earlier there was a problem with the pre work accuracy and thermal distortions of thinner plates. If the plate thickness is 5 mm and the weld length is typically 12 m it is really difficult to hold the air gap in needed tolerances and the high heat input of traditional welding processes causes a lot of deformations of plates. Too big deviations in the air gap cause weld defects. For improving productivity there was a project where Tuomo Kontkanen did his master's thesis about implementing hybrid welding in shipbuilding. In this application, there is a normal 12 m wide SAW portal equipped with additional laser-MAG-hybrid for thinner plate thicknesses. In this portal is a smart seam tracking system for welding. This system controls the weld quality with varying gaps in the joint through real-time control on the basis of the gap width. This system controls that the air gap will not grow too big. Laser-MAG-hybrid process allows pretty wide gap width, but because of ship classification requirements only about half of those values got acceptable weld in tests. (Kontkanen, p. 105)

Analysing of this case gave the following results:

- Weld characteristics is straight butt weld with I-joint. Accuracy is normal workshop quality. This prefers some mechanized or automated transport of the torch.
- Welding process is designed to be hybrid-MAG-welding because of full penetration and high welding speed. Heat input of this process is moderate compared to some other processes. This means at least mechanization of intelligence *Level 2*.
- The piece is a big straight plate sheet and this causes problems with the straightness of the plate edges and problems with the deviation of the air gap. This requires at least the measuring of the air gap before welding and adjusting welding parameters according to those values. The best way to do this is an adaptive on-line system, otherwise a compromise between minimum and maximum gap is needed. This requires *Level 3*.
- The product amount of welds is big, which supports at least a mechanized system.
- Working conditions in a workshop are controlled so it is not limiting automation.
- Quality assurance requirements come from a third party, ship classification and are modified according to standards in co-operation with the third party.
- Seam finding and tracking are not absolutely necessary, because plate edges can be pre-set at the right position compared to the torch transporting line, but the weld groove must be measured before the start of welding.
- Reliability requirements for welding system are high but working conditions not very difficult.
- Payback requirement is tight because of the commercial situation on global markets.
- Other things that must be mentioned can be that this system minimizes the cost of filler metal because it is optimized according to the gap width. Suppliers for welding system must be reliable, experienced and well known.

Plate welding in a shipyard is now done with a portal machine where big, standard size sheets are joined together in welding position PA for a further working phase. The product of this system is a 12 meter wide but much longer plate. In this case productivity has increased and company is satisfied with the result. System is in every day production and the optimizing of intelligence at *Level 3* is done exactly right. A numerical analysis of this case is presented in Table 6.5.

The welding of big plate sheets needs maximum efficiency for several plate thicknesses and welds are very long and straight. Manual welding is not productive enough and simple carriages may have difficulties with air gap tolerances. The system needs at least warning for too wide an air gap. A robot would be acceptable but there was a welding portal ready and possibility to reduce the costs of investment. For given plate thicknesses a laser-MAG-hybrid process gave the best productivity and for thicker plates there is still SAW. Adaptive option is reserved for the future but not yet quite necessary. So intelligence Level 3 seems to be high enough for this purpose.

Table 6.5 Analysis of case 5

Problem definition	**Intelligence level 1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	3	3	3	3	Straight, long, groove size vary, butt weld
2 Process	3	3	3	3	3	Laser-MAG hybrid + SAW
3 Piece	1	3	3	1	3	Big plate sheets
4 Amount	1	3	3	3	3	Mass production of welds
5 Conditions	3	3	3	3	3	Workshop
6 Quality	3	3	3	3	3	Ship classification
7 Seam find	3	2	3	1	3	Gap width may vary too much
8 Reliability	3	3	3	2	2	Must be high
9 Payback	1	2	3	1	1	Normal level
10 Others	1	3	3	2	3	Ergonomy/special robot
	22	28	30	22	27	Level 3 best

6.7 Case 6, Level 3: Welding of big cylindrical containers

This company increased their capacity by building a new factory and there they had to invest in welding automation. Their products are typically different containers, silos, chimneys, pressure vessels and heads of containers. Materials are normal construction steel and stainless steel for containers and silos and weather proof steel for chimneys. Cylindrical pieces may vary from diameters of 1 meter of chimneys to 8 meters of silos etc. and length from 1 meter of a small container to several ten meters of chimneys. Turning rolls are necessary for piece handling. Normal column and boom systems like presented in Figure 3.8 are used as a standard solution. Normal intelligence level of these systems is Level 2 or 3.

Analysing of this case gave the following results:

- Weld characteristics are easy straight or circle butt weld both sides without backing. Plate thickness from about 4 mm to 80 mm which can be rolled with a bending machine of a workshop. Normally welding only one bead on both sides is needed. This recommends at least the mechanization of Level 2.
- The best process which is well known, totally controlled, high experienced and productive and gives a sure result is SAW, with the best deposition rate. This means pretty easy automation possibilities but prefers welding position PA. Intelligence Level 2 or 3.
- The piece is cylindrical drum with diameters from 1 to 8 meters and length up from 1 meter to several ten meters like chimneys. This prefers remote control of arc with smart seam tracking.
- All welds are only butt weld with different plate thicknesses. The minimum length of one weld is about 1 meter and maximum several meters. Some kind of mechanized torch travel would be good, intelligence minimum on Level 2.
- Working conditions are a well controlled workshop, so it should not be too difficult for automation. There are no limits for the intelligence level.

- Quality requirements are normal. Inspection requirements vary according to the case. Again automatic torch travel would be good.
- Adaptive properties can be recommended because of weld groove accuracy and small deviation of gap width of really big plate dimensions is difficult to reach and outer side welding of big silo is done 8 meters up from the floor level and the operator should not climb up because of work safety. So remote welding would be good. Seam finding and tracking is necessary because of the same reasons.
- Reliability requirements for welding system are high but working conditions in workshop are not very difficult.
- Payback requirements are on normal level and that means few years.
- Other things like training of workers should not be a problem.

The welding of big cylindrical containers and big pieces show that adaptive properties are successful and competitive for welding in the height of several meters already because of work safety. SAW process is a pretty clear solution because of high productivity and welding system with boom and column is common and a well tested solution for these types of products. The maximum available intelligence is utilized to get the best productivity and usability. The optimized intelligence level of system is intelligence Level 3 because of difficult reaching of the weld in the height of several meters. Now company had economical resources to invest in the most modern technology and get an optimized welding system. When writing this dissertation adaptive filler feed was under testing by the system manufacturer. Then it can be said that the intelligence of system was actually on Level 3 and optionally coming to Level 5. Numerical analysis is presented in Table 6.6

Table 6.6 Analysis of case 6

Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	3	3	3	3	Straight or big circle, butt weld
2 Process	1	3	3	3	3	SAW, MMA
3 Piece	1	2	3	1	3	Big cylinder, 8 m up from floor
4 Amount	1	3	3	3	3	Need big deposition rate
5 Conditions	3	3	3	3	3	Workshop
6 Quality	2	3	3	3	3	Pressure vessel
7 Seam find	2	2	3	3	3	Remote welding
8 Reliability	3	3	3	3	2	Must be high
9 Payback	1	2	3	1	1	Best productivity, cost effectiveness
10 Others	1	2	3	1	3	Ergonomics, working in height of 8 m
	18	26	30	24	27	Level 3 best

Technical aspects give optimum intelligence Level 3, welding with sophisticated seam tracking would be the best for this case. When looking other aspects like an economical one and earlier experiences in other similar cases, the company decided to invest in modern welding boom and column with intelligence Level 3.

It is equipped with telescopic boom with adjustable length from 1 meter to 12 meters (with total possible telescopic length of even 16 meters) and column height of about 10 meters. This allows welding of piece diameters from 1 meter to 8 meter and horizontally 12 meters longitudinal weld by drawing the telescopic boom in. This telescopic system is shown in Figure 6.10 and the whole system in Figure 6.11.

Figure 6.10 Three component telescopic boom of modern welding boom and column system. (H.Salkinoja, courtesy of Saarijärven säiliövalmiste Oy)

Figure 6.11 SAW boom and column type SLv Welding Automation AW 8x12 welding inner bead of a big container. (H.Salkinoja, courtesy of Saarijärven säiliövalmiste Oy)

This system has a computer vision system for rail tracking, two video cameras and as an optional possibility for adaptive filler wire feed. First video camera shows the welding groove just before the arc and the second after the arc, so that the welder can see the result of the work. During the writing of this dissertation the system manufacturer was developing an adaptive system for this boom and column system. The productivity of this system is much higher than manual welding and the quality of welds is good because of mechanized torch transport.

This type of products requires an assembling stand for manual welders or mechanized lifting system for the torch with seam finding and tracking. A robot would need a really big working area. Typically the most economical solution for this problem has been a column and boom construction. Now the accuracy problems of pre work can be handled too.

The welding of big cylindrical containers is normally done with manual welding, mechanized torch carriers and with boom and column systems. All these can still be used but because of high labour costs and higher productivity requirements new technology was selected. The computer vision system can make the work easier. The actual result of Level 3 is good if we look at the common level of modern technology. Pure adaptive control is not quite yet reliable enough to be commercially available by several system manufacturers. Most of totally adaptive systems in welding seem to be still more or less prototypes or preliminary serial products. The best compromise is on Level 3. The robot does not fit well for this type of production and adaptive systems were not yet available for a reasonable price.

6.8 Case 7, Level 4: Welding of a round wood railway wagon frame

One rolling stock constructor had to produce a big series of round wood wagons for railways. This railway wagon type is a special design for round wood transport and has a totally new welded box-type steel structure. The amount of series was in the beginning several tens of wagons and later doubtlessly much more. The company policy is to produce wagons efficiently, quickly and economically. They have designed modular constructions, so the same components can be used in different wagon types like container, chopped wood and other bulk material transport types. This way they can increase batch sizes and get benefit in production. The main components of the wagon are a long middle frame structure with frames in ends, where the bogies with wheels are fixed. Then there are stud components to support wood bundles and end gratings.

The middle frame was really a challenging component to weld, because it first had to be cambered and it is a relatively complicated construction with several stiffener plates. The length of this component is about 11 meters. Assembling must be done in a welding fixture and start from the bottom or top plate and then join the other plates together. At least tacking must be done in this fixture. Final welding can be done in the same or separate fixture with a more sophisticated and more productive welding system. Both ends are typical box-type steel plate constructions with plenty of stiffeners. The end frame is about 3.5 m long and 2.5 m wide. In the workshop there was already a gantry with a welding robot and positioners. It was designed for welding the ends of the wagon frames. So it was clear to use this for welding the ends of frames and bogies. So intelligence level of this welding system was Level 4. The problem of this system is the size of the piece which does not allow the welding of a long middle frame. In Figure 6.12 a typical heavy duty welding gantry is presented.

Analysing of this case gave the following results:

- Weld characteristics vary in length but are mainly straight.
- The best process which is well-known, totally controlled, high experienced and gives a sure result with low process costs is MAG, which means pretty easy automation possibilities.
- The piece is a complicated box-type frame, which needs the space of approximately 12 m x 1.5 m x 1.5 m in welding fixture. Several stiffener webs and bended plates. Construction material is weldable construction steel.
- The product amount of welds is big, which supports at least a mechanized system.
- Working conditions are a controlled workshop, so it should not be too difficult for automation.
- Although fatigue loading conditions are in use, quality requirements do not need special grinding or other difficult finishing processes. Mainly normal welding class C and D.
- Seam finding and tracking are necessary if a robot is used. Adaptive properties can be avoided by the high enough accuracy of the pre work in bevelling and cutting of plates. Already pre worked plates are supplied by a subcontractor.
- Reliability requirements for the welding system are high but working conditions are not very difficult.
- Payback requirements are on a normal level.
- Other things like the training of workers should not be a problem because robotic welding already is used in the workshop. The supplier for the welding system must be reliable, experienced and well-known.

Figure 6.12 Heavy duty welding gantry with a hanging robot assembling (H.Salkinoja, courtesy of Naaraharju Oy)

The writer of this dissertation was as academic supervisor for Keijo Koistinen in his final project where he compared how different the welding techniques are in economical, quality and welding technical aspects in welding of the middle part of this frame. Also he examined module techniques and charted the best welding system to produce these frames. (Koistinen) Koistinen examined different welding methods and possibilities of robotics and mechanics and compared the costs of them. This thesis recommends a welding robot because a comparison between manual welding, welding carriage and robot show that the duty cycle alone show that the most effective welding system was a robotic welding. The duty cycle of manual welding was calculated to be about 20 %, welding carriage has about 40 % duty cycle and robot welding somewhere between 60 % to 80 % depending on the size of series. In the workshop there is already one robot welding system and the workers know how to use it efficiently. With robotic welding it is possible to reach the maximum deposition rate, safe piece handling and more continuous welds which improve quality. According to Koistinen the best system was a gantry with a welding robot with a pair of one axis positioned tables and a welding fixture where the frame is under the welding work. The properties of the robotic system were defined by using the drawings of a piece and co-operation with supervisors and according to this information the equipment supplier made a budget offer for a welding system. According to this an investment proposal could be done. Graphical simulation was not necessary because of large series.

Case 7 is typical plate construction and the evaluation system created, proposed robot welding to improve productivity and technically it is the correct solution. Deposition rate can be increased and duty cycle can be some two or three times higher than with manual welding. Adaptive properties are not necessary because most welds are filled welds and made in position PA or PB and seam finding and tracking systems of robot work today are reliable enough. Now controlling of pool and size of cross section of weld is not difficult when bevelling and volume of weld can be said to be relatively constant. Now it is not a problem to optimize the welding parameters for a robot and this means that the quality of weld stays constant and can be kept high enough. Numerical analysis of this case is presented in Table 6.7.

When writing this dissertation the company has not yet made an investment for a new robotic welding system but is producing these frames by using manual welding and with welding carriages. The method is to assemble the frame in a horizontal welding fixture which can be rotated around a longitudinal shaft to get better and easier welding positions. This welding fixture is later possible to use as a tag welding fixture for a robotic welding system. There is other welding fixture for the final assembling of the whole wagon where pre assembled main components will be joined together. In this way it is guaranteed that the accuracy of all components and the whole frame can reach the requirements. In this case intelligence Level 4 is found out to be the best optimization for productivity and quality. Before robotic investment intelligence Level 2 is used mechanization, for longitudinal welding and Level 1, manual welding, for other, shorter and more difficultly attainable welds.

Table 6.7 Analysis of case 7

Problem definition	Intelligence level 1	2	3	4	5	Comment
1 Weld	3	3	3	3	3	Fillet welds, PA,PB,PF mainly
2 Process	3	3	3	3	3	MAG, (SAW)
3 Piece	1	2	2	3	3	Heavy raiway wagon frame
4 Amount	1	2	2	3	3	Serial production, model variants
5 Conditions	3	3	3	3	3	Workshop
6 Quality	3	3	3	3	3	Vechile level, C
7 Seam find	2	2	3	3	3	Makes work faster
8 Reliability	3	3	3	3	2	Must be high
9 Payback	1	2	2	3	2	Depends on orders of customers
10 Others	2	2	2	2	2	Not special
	22	25	26	29	27	Level 4 best

A railway wagon frame was a different product compared to the others. Now there were several different types of welds and several welding positions. Welds were mainly straight with many corners and the piece was collected from plate components. In any case tag welding was most easily and most reliably done in a welding fixture by manual welding. For productivity a robot (intelligence Level 4) with working area big enough for the whole frame is the best solution if we have to produce big series of wagons. Economical limits caused by an economical depression period have prevented big robot investment so there are still welding torch carriers used with intelligence Level 2 for longer straight welds. The rest is welded manually.

In quality control we must remember fatigue load coming for the wagon frame in use, but this is already taken into account in designing the construction. The life time of the wagon frame can be several decades under heavy loads, so designing requirements are tight. After all we can say that company has selected the optimum intelligence level in the welding system when taken into account all productive, quality and economical aspects.

6.9 Case 8, Level 4: Intersector Welding Robot for ITER vacuum vessel

Assembling of International Thermonuclear Experimental Reactor (ITER) vacuum vessel is an especially challenging work. Vacuum vessel has nine 12 meters high sectors, wall thickness is two times 60 mm and between them there is a space. The material is stainless steel AISI 316L and the mass of 200 ton. In Lappeenranta Technical University is under construction an Intersector Welding Robot (IWR) with ten degrees of freedom for manufacturing of this vessel. The construction of this robot is presented in Figure 6.13.

Because there is a risk for hot cracking of weld and accuracy requirement of construction is ±5 mm. this robot must be able to machine metal too (H.Wu et al). When removing hot cracking the weld must be milled open and welded again. The last machining of holes in the inner wall of the vacuum vessel will be made with this robot. So the robot must be rigid under high loads and there are one welding head and two different milling heads designed for this robot. One milling head is for opening broken weld with saw type cutter and the other for finishing the holes of the inner wall with a shank cutter. The constructional model of the robot in the vacuum vessel is shown in Figure 6.14 and the welding head model is presented in Figure 6.15.

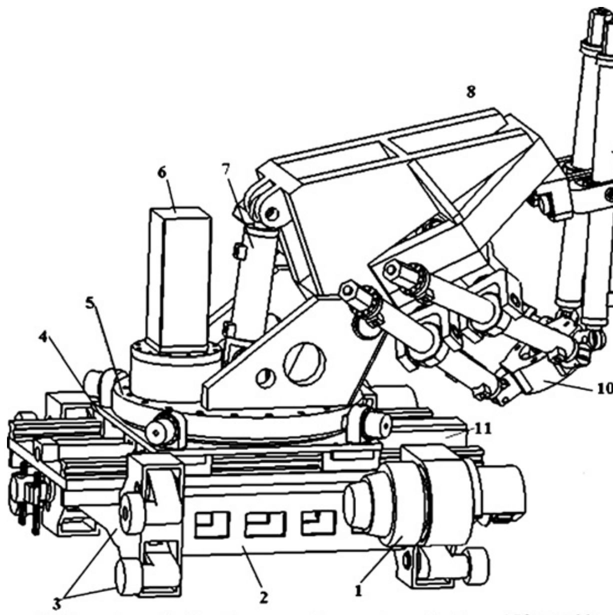


Figure 6.13 Intersector Welding Robot (IWR) (Pessi et al)

The analysing the results of this case outlined as follows:

- Weld characteristics have very high accuracy, narrow gap welding with different welding positions, not possible to weld manually.
- The best process was not yet designed but most promising seem to be Nd:YAG laser-metal arc hybrid which mean automatic welding at least Level 3, prefer ably even Level 5.
- The piece is a complicated, very heavy and extremely high accurate stainless steel construction and this require at least mechanization with sophisticated seam tracking.
- The product amount of welds is big, which support at least the mechanized system.
- Working conditions are very controlled so they are not limiting automation.
- Quality assurance requirements are perhaps the most demanding in the world and no failures are allowed. A human error is not allowed at all. This means as automatic a process as possible.
- Adaptive properties can be recommended but they are not absolutely necessary because the welding groove must have a much better machining quality than normal.

Seam finding and tracking must be very sophisticated because of quality requirements and this prefers Level 3 or higher.
- Reliability requirements for the welding system are high but working conditions are not very difficult.
- In this special case payback requirement does not have any important role because the work just must be done and because the project is so necessary for the whole world.
- There is a need for very high accuracy metal cutting with the same system and this need to select a very rigid robot. On the other hand later during the maintenance work of reactor all work must be done with the remote control because of radioactive radiation and this means at least a robot level of intelligence. Suppliers for welding system must be reliable, experienced and well known. The best know-how of the world can be used in this case.

ITER vacuum vessel is just too exact work for a manual welder because of its high accuracy and really unique and special case where economical aspect is not so determinant. The problem is just to make acceptable weld and have a later possibility to make repair work with a remote control in radiating circumstances. As a result of analysis there is a minimum intelligence Level 4 which can be accepted when welding this piece. In Table 6.8 is presented numerical analysis of the case.

Table 6.8 Analysis of case 8

Problem	**Intelligence level**					
definition	**1**	**2**	**3**	**4**	**5**	**Comment**
1 Weld	2	2	3	3	3	Need special torch
2 Process	3	3	3	3	3	TIG,MAG,Hybrid
3 Piece	0	0	0	3	3	Automatic repair welding
4 Amount	1	2	2	3	3	Fit best for machine
5 Conditions	0	0	0	3	3	Later radiation
6 Quality	1	2	3	3	3	Must be sure
7 Seam find	0	0	3	3	3	Needed
8 Reliability	1	1	3	3	2	Absolutely sure
9 Payback	1	1	1	1	1	No problem
10 Others	0	0	1	3	2	Too tight tolerances for MMA
	9	11	19	28	26	Level 4 best

As the final result of analyzing this case we can state that intelligence Level 4, robot welding is the most suitable level for the welding system of the vacuum vessel of ITER reactor.

The Intersector Welding Robot for ITER vacuum vessel is needed because that work is not possible to do without high intelligence and accuracy of automation. The system is now optimized for remote control because there may later be a need for repair work in radiating conditions. This case is a special case in the economical side because we can say that payback time is not important. If the system just works, it is good.

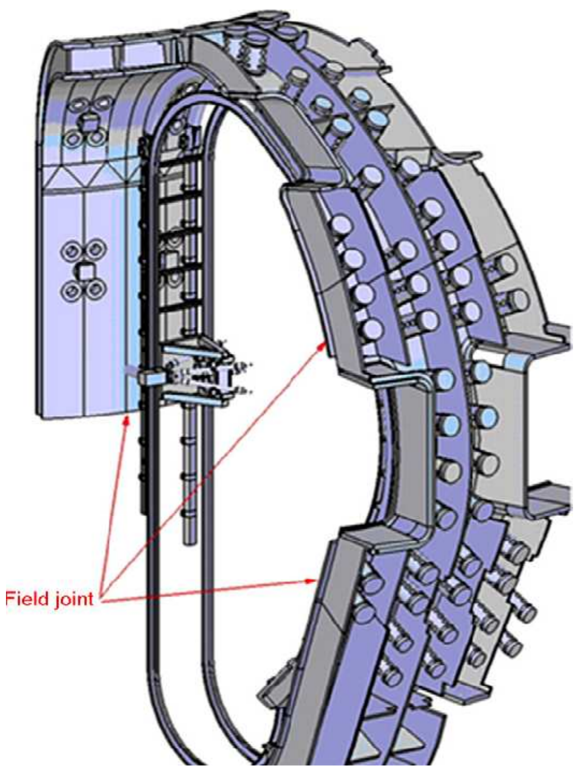


Figure 6.14 Intersector Welding Robot (IWR) in the ITER vacuum vessel sector (Pessi & al)

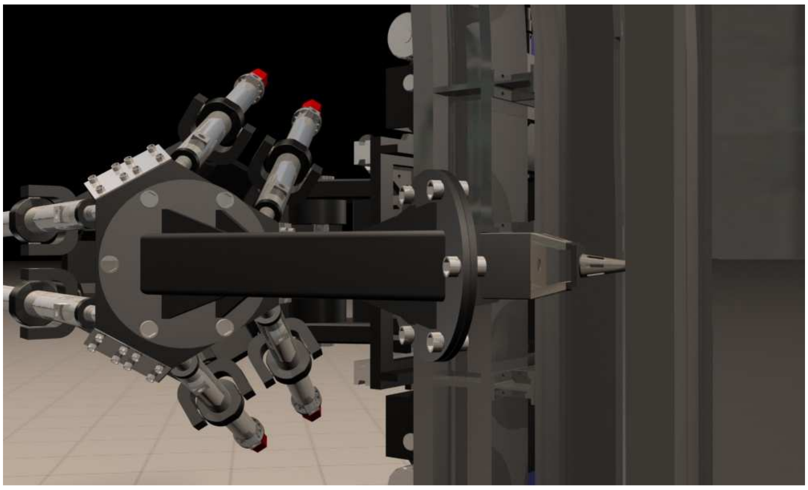


Figure 6.15 Intersector Welding Robot with welding head. (LUT, H. Handroos)

6.10 Case 9, Level 5: Narrow gap welding of steam turbine rotor

Figure 6.16 shows a steam turbine rotor that has very high requirements and it is complicated to make. In this case it was necessary to join chromium-molybdenum-vanadium to nickel-chromium-molybdenum-vanadium forgings. Welding was made between high- and intermediate-pressure parts which were joined to a low-pressure part. The rotor was 6 m long and outer diameter was about 700 mm. Wall thickness was 150 mm, and groove width was selected 7 mm. Process was narrow-gap hot-wire TIG because of better efficiency. This process requires sophisticated seam tracking because weld must become exactly at the right place in a narrow and deep welding groove. The problem is low penetration to groove walls and there must be two beads alternatively parallel in the bottom of the groove. There exists a commercial system on the market with visual sensors but it needs too much manual intervention by the worker. Now there was developed an automatic, narrow-gap hot wire TIG unit without a monitor for pipes with a CCD camera and a laser sensor on the welding head. This system idea is presented in Figure 6.16. Before the welding starts, the laser sensor measures the shape of the groove to teach the welding line for the system and establish welding conditions. A typical narrow gap weld in Figure 6.17 is presented.

During welding, the images of the weld pool and its periphery taken by the CCD camera are processed, the positions of the electrode and wire are automatically corrected, and the welding conditions are controlled adaptively. Another function of the system measures the bead shape after welding to detect undercut, unevenness, and wetting angle errors automatically. This system can be classified to intelligence Level 5 according to the criteria of this thesis.

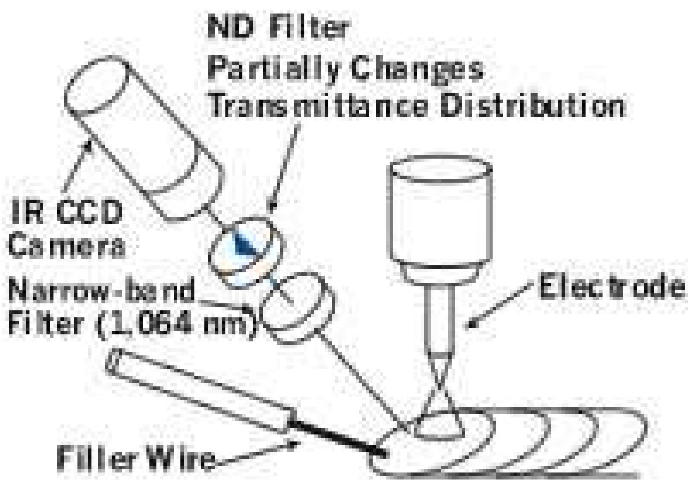


Figure 6.16 Filtering system developed for CCD camera and seam tracking. (Asai et al.)

Figure 6.17 Macroscopic picture of narrow gap weld of 100 mm thick pipe wall (Polysoude)

Analysing of this case gave the following results:

- The weld itself is an easy circle but must be made in narrow and deep groove, outer diameter 700 mm and wall thickness 150 mm. It is not easy to control welding conditions in a deep groove. Minimum possible Level 2 of intelligence but adaptive system fits best. So recommendation is Level 5.
- The best process which is well known totally controlled, high experienced and gives sure result is TIG with hot wire application because of higher productivity. This means pretty easy automation possibilities. Minimum Level 2 of intelligence.
- The piece is a complicated big turbine rotor, length 6 m. At least mechanization must be recommended.
- The product amount of welds is not very big but the product is expensive. No limits for intelligence but weld must be good. This recommends some method and process which gives sure results.
- Working conditions are a controlled workshop, so it should not be too difficult for automation. All intelligence levels work here.
- Quality requirements need totally high quality for the weld because work piece is a critical component of a whole power plant. That is the reason for camera assisted adaptive control of welding conditions.
- Seam tracking is necessary. Reliability requirements for welding system are high but working conditions are not very difficult. Because of this, weld need on-line monitoring with a CCD-camera or some other measuring method and computerized adaptive controlling for the process. Intelligence Level 5 is necessary.
- Reliability of the system must be good because the weld must be excellent, too.
- Payback requirements are on a normal level.
- Other things like the training of workers should not be a problem. No special requirements for intelligence.

A thick wall cylinder joined with narrow gap welding was selected because of smaller thermal distortions, smaller weld volume and this way faster welding work. Adaptive control is needed because of a narrow and very deep welding gap where the arc must get good weld at exactly the right place and get the right shape. In this case a good result was reached when creating a new sophisticated welding method with an optimized intelligence level for a really demanding welding problem of a turbine component. Numerical analysis of this case is presented in Table 6.9.

Table 6.9 analysis of case 9

Problem definition	**Intelligence level 1**	**2**	**3**	**4**	**5**	Comment
1 Weld	0	3	3	3	3	Fit best for mechanization
2 Process	3	3	3	3	3	TIG
3 Piece	1	2	3	3	3	Fit best for mechanization
4 Amount	1	2	3	2	3	Fit best for mechanization
5 Conditions	0	0	3	2	3	Camera/special robot needed
6 Quality	0	0	3	3	3	Not possible without camera
7 Seam find	0	0	1	1	3	Need adaptive system
8 Reliability	0	1	2	3	3	High
9 Payback	1	1	2	2	2	Normal level
10 Others	0	0	2	2	3	Best available is adaptive
	6	12	25	24	29	Level 5 best

The analysing gives an optimum area for intelligence Level 5 and it presents sophisticated seam tracking with pool monitoring and full adaptive system because it controls the welding conditions adaptively. Another function of the system measures the bead shape after welding to detect undercut, unevenness, and wetting angle.

Narrow gap welding is already a normal method in thick wall tube-type part joining. Rotor is really a demanding part and thickness of 150 mm is on the upper area of narrow gap welding applications. Because of these reasons calculations gave the best solution for intelligence level to be the adaptive steering of the process. If welding had been made with the blind system by setting each pass at the bottom of the groove, there would have been a really big risk for welding failures. In this case repair work of welding failures is really difficult and may easily spoil the whole work. The weld must be opened much wider than the original gap has been and the risk of too big thermal distortions is high.

6.11 Case 10, Level 5: Laser guided welding travel carriage

In this case two companies, one domestic shipyard and another company in Turkey had similar problems in welding of big plate sheets; several meters long straight welds and difficulties to reach tight tolerances of welding groove and especially air gap. There is a real need of adaptive, mechanized or automated system which can produce a good weld in spite of the varying air gap. Other possibility is manual welding but it has too low productivity. On the market came a laser guided welding travel carriage where a separate laser control unit is combined with a standard rail guided welding travel carriage. This type of a carriage is already shown in Figure 3.26.

The analysing the results of this case outlined as follows:

- Weld characteristics is straight weld with butt, fillet or lap joint. Accuracy is normal workshop quality so the air gap can vary too much for constant parameters. This prefers both manual and adaptive welding. Here adaptive welding of Level 5 has better productivity.
- The welding process is designed to be MAG because it is an easy process for mechanization and productivity is on an acceptable level. This means at least the mechanization of intelligence Level 2.
- The piece is a big straight plate sheet and this causes problems with the straightness of plate edges and problems with the deviation of the air gap. This requires at least measuring of the air gap before welding and adjusting welding parameters according to those values. The best way to do this is an adaptive on-line system, otherwise a compromise of parameters between a minimum and maximum gap. This requires the adaptive welding of Level 5.
- The product amount of welds is big, which supports at least a mechanized system of Level 2.
- Working conditions in a workshop are controlled and should not limit automation. On the other hand in the shipyard there is welding outside in the wind and rain. There MAG is not a good process.
- Quality assurance requirements come from a third party, like ship classification and are according to standards. There are no special requirements of intelligence level.
- Adaptive properties are now strongly recommended because of productivity requirements.
- Seam finding is not needed but seam tracking is, because plate edges can be a little curved caused from the low accuracy of pre work.
- Reliability requirements for welding system are high but working conditions are not very difficult.
- Payback requirements are tight because of the commercial situation on global markets.
- Other things that must be mentioned can be that this system minimises the cost of filler metal because it is adjusted according to the gap width. Suppliers for welding system must be reliable, experienced and well known.

Now according to this analysis adaptive control of arc is the best optimum of intelligence for this type of welding work.

The laser guided welding travel carriage is an excellent solution when welding big plates together and where typical welds are long and straight but the welding position may vary from PA to PF. Intelligence optimization gives the most productive level to be Level 5, adaptive welding. Later the reliability of system has become a problem. It works well in laboratory conditions but again in real workshop it does not work as designed. For instance bright sunshine or welding arc can disturb the laser. It seems that this technology is not yet reliable enough to be used in difficult environments. On the other hand, this machine allows such a good combination of properties for production welding that many companies are really interested in it. Numerical analysis of this case is presented in Table 6.10.

Table 6.10 Analysis of case 10

Problem definition	**Intelligence level 1**	**2**	**3**	**4**	**5**	Comment
1 Weld	3	1	1	1	3	Big variation of groove size
2 Process	3	3	3	3	3	All metal arc fit
3 Piece	1	3	3	2	3	Mainly long welds
4 Amount	1	3	3	2	3	Big working area
5 Conditions	3	3	3	1	3	Workshop or site
6 Quality	2	2	3	1	3	Easiest to reach
7 Seam find	2	2	3	3	3	Adaptive best
8 Reliability	3	3	3	2	2	Best simple
9 Payback	1	3	2	2	2	Normal level
10 Others	3	1	1	1	3	Best adaptivity
	22	24	25	18	28	Level 5 best

This case has different requirements because there the piece can already be assembled to bigger construction and welding position may vary. Technically and economically (one operator can use two machines at the same time, pay back time one year) this system is excellent. Sunshine may disturb the laser because both are light and reflections cause problems for the function of the system. In good conditions it seems to be very effective especially for ship manufacturers and similar production. Adaptive welding combined with simple mechanized torch travel is something that the industry really needs.

7. DISCUSSION

If we look at the special features of welding like the productivity of the system, reliability of welds and in welding work, quality and quality assurance, standards, safety etc areas in each case, we can say that these aspects must be taken into account.

If the intelligence of the welding system investment will be selected too high, there will be problems in the reliability of the system functioning, the production speed may decrease from the designed and the quality level of welds cannot be kept steady. The usability of the system becomes difficult, problem shooting more demanding and the professional skills of operators must cover computers, too. The price of investment increases very rapidly and there are serious risks seen for the business and the possibilities to reach the intended payback time. Many times old manual welding is still able to compete.

If too low a level is selected, productivity stays low, an unintelligent machine works blindly, a worker is needed as a controller and maybe this is not faster than manual welder. In manual welding it is very difficult to keep the quality level steady and high enough all the time. The total productivity of work will stay low and costs become high.

The mechanized transport of arc gives normally a much smoother welding bead surface, can use higher welding parameters and can be recommended in most cases to replace manual welding but require better pre-work. On the other hand the most flexible method is traditional manual welding, because that system is the most adaptive too. Case 1 and case 2 show that sometimes it is the best optimum of the intelligence level of a welding system. Manual welding has its strengths and its weaknesses like better flexibility but lower deposition rate and productivity compared to mechanized or automated processes. Still it is clear, that seam finding and tracking release the operator from the boring work to follow that the machine really makes the weld bead at the right place. This is important, if welds are in difficult places for a manual welder to reach like in case 8 or they are really long or somehow other way boring. Robots are often used in these types of heavy and boring work. It has its own advantages, but the investment is often underutilized and that’s why not really profitable. Adaptive welding helps when the accuracy of the pre work of the parts is not good enough or conditions are for instance not suitable for a human worker. This increases the price and makes the system more complicated and sets high standards for the reliability and robustness of the system.

When evaluating earlier classifications of the intelligence level of welding systems, it can be seen that they do not fit well for optimizing the best intelligence level for a welding system. The minimum sensible amount for intelligence levels is five. If there were fewer levels, the scale would be too coarse. Two levels mean only a manual and somehow mechanized or automated system. Three levels are still too coarse. Now there would be manual systems, mechanized systems and automated systems. The question is still, how smart automation or mechanization is the best. Four levels do not divide systems in quite a clear way, but five levels do it clearly, unambiguously and in an easy way. This classification contain all different torch transport ways and classifies systems to manual systems, systems with blind mechanical transport, torch transport systems with seam tracking or NC, welding robots and adaptive welding systems. Six or seven levels, like Cary and Martikainen have used, are already too fine-grained and optimizing process grows complicated. Cary and Martikainen separate manual and semiautomatic systems and in this dissertation they are included in Level

1 because for the investment there is not so big a difference between them (MMA or MAG) and Martikainen has divided adaptive welding into two groups according to optimizing the productivity and quality. These classifications are no more so handy and easy, possibility for mistakes grows and the result may be wrong. With five levels it is easy enough to find a suitable intelligence level. These are the reasons why just the five-level classification is the best and used in this study.

For further study a wider survey could be made about welding systems in domestic and foreign welding workshops and analyze them with this new method. Especially there should be analyzed how close the best optimum intelligence level is when compared to the used welding systems. After this there should be analyzed the reasons why there are differences between this new theory and the real practice of workshops. Then these results should be utilized in the Finnish industry. This way it is possible to develop the competitiveness of the domestic welding industry.

Also it could be useful to study and develop the sensor technology used in welding and the usability of welding monitoring systems more humane for the user. Modern computers and their programmes are often too complicated and difficult for a normal worker and in fact, are not used in daily work. Their efficiency is mostly good enough and programmes can be developed suitable for the monitoring and adaptive welding process. A really easy system with clear effect on productivity is still waiting for its inventor.

8. CONCLUSIONS

A simple systematic method for the optimizing of intelligence level in welding has been created. It was proven in this study that there are clear limits in the optimum level of intelligence in a welding system that can be found.

When looking into cases and the results calculated from them, it can be seen that in each case the best intelligence level is found on the grounds of economical productivity, batch size of products, quality and criteria of usage.

On the basis of the results of this research the following conclusions can be drawn:

A new optimizing method for calculating the best optimum for the intelligence level of a welding investment is developed.

This calculation method is based on the needs of product, its technical, economical and quality aspects. Also the batch size and ergonomics are taken into calculation.

A totally new classification for the automation and mechanization levels of welding systems is developed, based on the system ability to produce a good weld productively. Earlier classifications were created only for hard technical components and functions and they do not speak out any human aspects.

It is proven that by calculating the best optimum of the needed intelligence with the optimizing method developed in this study, the profitability of a welding investment can be optimized.

As the final result it is found how important it is to systematically optimize the intelligence level of a welding system investment. This way the company can make a successful investment and effectively improve the productivity of the welding work.

In the point of view of the industrial feasibility, this optimizing method has its own advantages to reach predetermined effectiveness in welding. This modern and simple optimizing method is relatively reliable, simple and easy to use. It will help industries select the exactly right welding system for their needs.

REFERENCES

Published documents

Aaltonen P., Hakala J., Ydinvoimalaitosten vaativien ruostumattomista teräksistä valmistettujen komponenttien hitsaus.(Welding of demanding stainles steel made components of nuclear power plants. In Finnish) Hitsaustekniikka 2004.Vol.54:6

America. Vision for Welding Industry. 550 LeJeune Rd. Miami, FL 33126

Barkhoff J.R., Total Welding Management, American Welding Society, 2006,Vol 5

Bug-O-Systems, Laser-Bug Instruction manual, MEL Mikroelektronik GmbH, 85386 Eching/Germany

Cary, Howard B. Helzer, Scott C., Modern Welding Technology, Sixth edition, Pearcon Prentce Hall, 2005, ISBN 0-13-113029-3

Chadwick Leslie, Management Accounting, Second edition, International Thomson Business press, Berkshire House, 168-173 High Holborn, London WC1V7AA, UK, 1993, 1998, ISBN 1-86152-260-6

Christensen, N., Davies, V. de L. and Gjermundsen, K. British Welding Journal, 12.

Energetics Inc. Columbia, MD, The American Welding Society, The Edison Welding Institute. Welding Technology Roadmap, Final Draft September 2000, The U.S. Department of Energy Office of Industrial Technologies

Jernström Petteri, The effects of real-time control of welding parameters on weld quality in plasma-arc keyhole welding. Acta Universitatis Lappeenrantaensis 102, Diss. Lappeenranta University of Technology. ISBN 951-764-479-5

Koistinen Keijo, Raakapuuvaunun keskirungon hitsausmenetelmän kehittäminen, (Developing the Middle Frame Welding of the Raw Tree Car), Final thesis, Savonia University of Applied Sciences, Business and Engineering, Varkaus. 2007.

Kontkanen Tuomo, Laser-MAG-hybridihitsauksen käyttöönotto laivan rungon valmistuksessa. (Exploiting of Laser-MAG-hybrid welding in manufacturing of ship hull. In Finnish). Lappeenranta University of Technology, Department of Mechanical Engineering, Master thesis, 2007.

Lancaster, J.F., Metallurgy of Welding, Sixth Edition, Abington Publishing Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB 1 6 AH, England, 1999,
ISBN 1-85573-428-1

Leino Kalervo, Pienten kiinteäasentoisten putkien mekanisoitu TIG-hitsaus, (Mechanized TIG-welding of small fixed tubes. In Finnish) Tekninen tiedotus 14/85, Metalliteollisuuden Keskusliitto 1985,38 pages, ISBN 951-817-258-7

Lukkari Juha, Hitsaustekniikka - Perusteet ja kaarihitsaus, (Welding technology-Fundamentals and arc welding. In Finnish), Opetushallitus, 4.p, 1997, ISBN 952-13-1409-5

Martikainen Jukka, Hitsauksen jatkokurssi. (Lessons of advanced welding technology course), Lappeenranta University of Technology, 2007.

Salkinoja H., Martikainen Jukka, Technical and economical aspect to improving productivity and efficiency of welding of critical constructions with more effective processes, low-cost mechanization and automation. 3rd Join Conference on Total Welding Management in Industrial Applications, Lappeenranta, August 21 – 24, 2007.

Results of Brain Storm in Refresher course of welding coordinators, LUT, Lappeenranta, (In Finnish) 8.-9.2005

SFS-EN 1011-2, Welding. Recommendations for welding of metallic materials. Part 2: Arc welding of ferritic steels.

SFS-EN 1792, Welding. Multilingual list of terms for welding and related processes.
Suoranta, Raimo. MIG/MAG-hitsaus. (MIG/MAG welding. In Finnish) Hitsaustekniikka, 2007. Vol.57:2. ISSN 0437-6065

Suthey Holler Associates, A Vision for Canadian Welding Industry, The Canadian Welding Industry, 2004, ISBN 0-9733935-1-3

Tarn T.J., Chen S.-B., Zhou C.; Robotic Welding, Intelligence and Automation, Springer – Verlag Berlin Heidelberg New York, 2004, ISBN 3-540-20804-6

TTKK, Lectures of welding technology. Technical University of Tampere 1987

Uusi-Rauva E.,Tuottavuus - mittaa ja menesty, Kauppakaari Oy, Yrityksen tietokirjat, Helsinki 1997, ISBN 951-640-958-X

Welding Handbook, Vol. 1, 9th edition, American Welding Society, 2001, 918 p.

Welding Handbook, Vol. 2, 9th edition, American Welding Society, 2004, 720 p.

Network documents

Arc Machines Inc (Read 16.6.2008) Available:
http://www.arcmachines.com/BrochurePDFs_English032502/Model77_E.pdf

Artsautomotive (Read 18.10.2008) Available: www.artsautomotive.com/machineservices.htm

Asai S., Taki K., Ogawa T.: Using narrow-gap GTAW for power-generation equipment Techniques and applications. Practical Welding Today® Contributing writers April 10, 2003 (Read 2.11.2008) Available:
http://www.thefabricator.com/ArcWelding/ArcWelding_Article.cfm?ID=552

AVP (Read 20.6.2007) Available:
http://www.avp.si/?mod=catalog&action=productDetails&ID=19

Brainerdrops (Read 18.10.2008) Available:
www.brainerdprops.com/images/before-after.jpg

BUG-O (Read 19.6.2007) Available: http://www.bugo.com/pdf/bug-gy-vert%203000.pdf and http://www.bugo.com/pdf/laserbug.pdf

Cypressweld. (Read 19.6.2007 and 27.9.2008) Available: http://www.cypressweld.com/cw-11.htm and http://www.cypressweld.com/cw-5.htm

DOCKLASER (Read 24.9.2009) Available: http://ec.europa.eu/research/industrial_technologies/articles/article_1851_en.html

D.L.Ricci Corp. Facers and End Preps. (Read 24.1.2009) Available:
http://www.dlricci.com/face2.htm

EnviroKinetics Inc, waste heat recovery (Read 24.1.2009) Available:
http://www.envirokinetics.com/

ESAB. Product catalogue. (Read 30.7.2005). Available http://www.esab.fi/.

Flickr flickr.com (Read 21.1.2009) Available:
http://images.google.com/images?ndsp=20&um=1&hl=fi&lr=&q=steam+drum&start=140&sa=N

Geog Fischer Piping Systems, Product catalogues. (Read 29.7.2005) Available: http://www.piping.georgfischer.com/index.cfm?76AD2D5261F04F06A9877EEEF17ECEA1

Kemec. (Read 26.9.2008) Available http://www.kemec.fi/pdf/Kn1000_fi.pdf

Kemppi. (Read 18.6.2007) Available:
http://www.kemppi.fi/inet/kemppi/en/akp.nsf/frameset/Frameset?OpenDocument&left=/inet/kemppi/en/akp.nsf/WEB_Nav?OpenView&navcat=Search&main=/inet/kemppi/frontpage.nsf/0/2D1C6A77EDA18CB0C225718400067C31?opendocument&top=/inet/kemppi/en/akp.nsf/Top?ReadForm&topcat=Product%20Info

Koike (Read 18.6.2007) http://www.koike.com/Machines/Machine.aspx?MachineID=437

Laserplus (Read 23.4.2008)
http://www.laserplus.fi/images/circweldingsys.pdf

Liburdi (Read 10.1.2009) Available
http://www2.liburdi.com/liburdidimetrics/products_ptw160.php

Miningindustrialengineering (Read 18.10.2008) Available:
http://images.google.fi/images?q=repair+welding%2Bcement+screw&btnG=Etsi+kuvia&um=1&hl=fi&client=firefox-a&channel=s&rls=org.mozilla%3Afi%3Aofficial&sa=2

NOMAD (Read 10.1.2009) Available: http://www.nomadrobot.org/

Peltola, T., Penetration control in MIG/MAG-welding, Master's thesis, Lappeenranta University of Technology, Faculty of Technology, Department of Mechanical Engineering, 2008. (Read 6.2.2009) Available https://oa.doria.fi/handle/10024/38665

PEMA (Read 20.6.2007) Available:
http://www.pemamek.fi/eng/products/?PAGE=4&KAT=19&PROD_ID=91

Pessi P., Wu H., Handroos H., Jones L., A mobile robot with parallel kinematics to meet the requirements for assembling and machining the ITER vacuum vessel. Fusion Engineering and Design 82 (2007) 2047–2054, (Read 24.1.2009) Available:
www.elsevier.com/locates/fusengdes

Polysoude, Product catalogue. (Read 30.7.2005). Available http://www.teknohaus.fi

Precitec KG, Remote sensor system (Read 24.4.2008) Available
http://www.precitec.de/precitec/enxml/products/lwm_remotesensorsystem.html

Rantanen Hannu, Productivity in the field of performance (Read 24.9.2009) Available:
http://www.lut.fi/fi/lahti/publications/2005/Documents/Tyopapereita%203%20Rantanen.pdf

Rausch W. and Koch M., Rheinische Bahngesellschaft AG, Düsseldorf, and Dipl.Ing. Paschold R., Esab GmbH, Germany J. Schattling, Resurfacing tramway rails. (Read 18.1.2009) Available:
http://www.esabsverige.net/global/en/products/upload/tramway.pdf

Sharma A., Junaidh M.I., Purushothaman K.K.,Kotwal C.P,Paul J.,Shalini Tripathi,Pant B. and Sankaranarayanan A.S., Online Monitoring of Electron Beam Welding of TI6AL4VAlloy ThroughAcoustic Emission,Proc. National Seminar on Non-Destructive Evaluation Dec.7-9,2006, Hyderabad, Indian Society for Non-DestructiveTesting Hyderabad Chapter (Read 24.4.2008) Available http://www.ndt.net/article/nde-india2006/files/tp-14-pap.pdf

Vietz. VPL-System®, Pipeline laser, (Read 4.4.2008) Available http://www.vietz.de/online-katalog-e/pdfs/Part%203E/3E_78_Vietz-Pipeline-Laser_VPL-System.pdf

Wu H., Handroos H., Kovanen J., Rouvinen A., Hannukainen P., Saira T., Jones L., Design of parallel intersector weld/cut robot for machining
processes in ITER vacuum vessel. Fusion Engineering and Design 69 (2003) 327_ 331 (Read 15.9.2008) Available www.elsevier.com/locates/fusengdes

Interviews and e-mails

Behlen Bernd B. interview and e-mails 11.2008

Peiponen, Jorma, interviewed 28.6.2007

Keinänen Jouko, Hoikkala Juhani, Koljonen Arto: interviewed several times 2006...2008

Meuronen, Ismo, discussions and e-mails during years 2002…2008

Takala, Rauno, e-mails 19.8.2008

Vainionpää Asko, Santamäki Marko, Askola Jarmo, interviewed 18 and 19.8.2008

Other references:

http://www.omegalaser.com/

http://www.tailored-blanks.com/de/produkte/produktionsprozess.jsp

https://portti.lut.fi/f5-w-687474703a2f2f6d6f742e6b69656c696b6f6e652e6669$$/mot/lty/netmot.exe

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

317. HAIMALA, JUHA. Supplier´s position in project marketing networks. 2008. Diss.

318. UOTILA, TUOMO. The use of future-oriented knowledge in regional innovation processes: research on knowledge generation, transfer and conversion. 2008. Diss.

319. LAPPALAINEN, TOMMI. Validation of plant dynamic model by online and laboratory measurements – a tool to predict online COD loads out of production of mechanical printing papers. 2008. Diss.

320. KOSONEN, ANTTI. Power line communication in motor cables of variable-speed electric drives – analysis and implementation. 2008. Diss.

321. HANNUKAINEN, PETRI. Non-linear journal bearing model for analysis of superharmonic vibrations of rotor systems. 2008. Diss.

322. SAASTAMOINEN, KALLE. Many valued algebraic structures as measures of comparison. 2008. Diss.

323. PEUHU, LEENA. Liiketoimintastrategisten vaatimusten syntyminen ja niiden toteutumisen arviointi keskisuurten yritysten toiminnanohjausjärjestelmähankkeissa: Tapaustutkimus kolmesta teollisuusyrityksestä ja aineistolähtöinen teoria. 2008. Diss.

324. BANZUZI, KUKKA. Trigger and data link system for CMS resistive plate chambers at the LHC accelerator. 2008. Diss.

325. HIETANEN, HERKKO. The pursuit of efficient copyright licensing – How some rights reserved attempts to solve the problems of all rights reserved. 2008. Diss.

326. SINTONEN, SANNA. Older consumers adopting information and communication technology: Evaluating opportunities for health care applications. 2008. Diss.

327. KUPARINEN, TONI. Reconstruction and analysis of surface variation using photometric stereo. 2008. Diss.

328. SEPPÄNEN, RISTO. Trust in inter-organizational relationships. 2008. Diss.

329. VISKARI, KIRSI. Drivers and barriers of collaboration in the value chain of paperboard-packed consumer goods. 2008. Diss.

330. KOLEHMAINEN, EERO. Process intensification: From optimised flow patterns to microprocess technology. 2008. Diss.

331. KUOSA, MARKKU. Modeling reaction kinetics and mass transfer in ozonation in water solutions. 2008. Diss.

332. KYRKI, ANNA. Offshore sourcing in software development: Case studies of Finnish-Russian cooperation. 2008. Diss.

333. JAFARI, AREZOU. CFD simulation of complex phenomena containing suspensions and flow through porous media. 2008. Diss.

334. KOIVUNIEMI, JOUNI. Managing the front end of innovation in a networked company environment – Combining strategy, processes and systems of innovation. 2008. Diss.

335. KOSONEN, MIIA. Knowledge sharing in virtual communities. 2008. Diss.

336. NIEMI, PETRI. Improving the effectiveness of supply chain development work – an expert role perspective. 2008. Diss.

337. LEPISTÖ-JOHANSSON, PIIA. Making sense of women managers´ identities through the constructions of managerial career and gender. 2009. Diss.

338. HYRKÄS, ELINA. Osaamisen johtaminen Suomen kunnissa. 2009. Diss.

339. LAIHANEN, ANNA-LEENA. Ajopuusta asiantuntijaksi – luottamushenkilöarvioinnin merkitys kunnan johtamisessa ja päätöksenteossa. 2009. Diss.

340. KUKKURAINEN, PAAVO. Fuzzy subgroups, algebraic and topological points of view and complex analysis. 2009. Diss.

341. SÄRKIMÄKI, VILLE. Radio frequency measurement method for detecting bearing currents in induction motors. 2009. Diss.

342. SARANEN, JUHA. Enhancing the efficiency of freight transport by using simulation. 2009. Diss.

343. SALEEM, KASHIF. Essays on pricing of risk and international linkage of Russian stock market. 2009. Diss.

344. HUANG, JIEHUA. Managerial careers in the IT industry: Women in China and in Finland. 2009. Diss.

345. LAMPELA, HANNELE. Inter-organizational learning within and by innovation networks. 2009. Diss.

346. LUORANEN, MIKA. Methods for assessing the sustainability of integrated municipal waste management and energy supply systems. 2009. Diss.

347. KORKEALAAKSO, PASI. Real-time simulation of mobile and industrial machines using the multibody simulation approach. 2009. Diss.

348. UKKO, JUHANI. Managing through measurement: A framework for successful operative level performance measurement. 2009. Diss.

349. JUUTILAINEN, MATTI. Towards open access networks – prototyping with the Lappeenranta model. 2009. Diss.

350. LINTUKANGAS, KATRINA. Supplier relationship management capability in the firm´s global integration. 2009. Diss.

351. TAMPER, JUHA. Water circulations for effective bleaching of high-brightness mechanical pulps. 2009. Diss.

352. JAATINEN, AHTI. Performance improvement of centrifugal compressor stage with pinched geometry or vaned diffuser. 2009. Diss.

353. KOHONEN, JARNO. Advanced chemometric methods: applicability on industrial data. 2009. Diss.

354. DZHANKHOTOV, VALENTIN. Hybrid LC filter for power electronic drivers: theory and implementation. 2009. Diss.

355. ANI, ELISABETA-CRISTINA. Minimization of the experimental workload for the prediction of pollutants propagation in rivers. Mathematical modelling and knowledge re-use. 2009. Diss.

356. RÖYTTÄ, PEKKA. Study of a vapor-compression air-conditioning system for jetliners. 2009. Diss.

357. KÄRKI, TIMO. Factors affecting the usability of aspen (Populus tremula) wood dried at different temperature levels. 2009. Diss.

358. ALKKIOMÄKI, OLLI. Sensor fusion of proprioception, force and vision in estimation and robot control. 2009. Diss.