WORK HARDENING OF ULTRA-HIGH-STRENGTH STEELS AND INFLUENCE OF TEMPERATURE ON THEIR STRAIN HARDENING BEHAVIOUR

Experimental work on S960MC and S1100

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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This study examines the behavior of ultra-high-strength steels, S960 and S1100, under high temperatures through tensile testing. The research aims to assess their mechanical capabilities and deformation traits. Tensile tests are conducted, and key mechanical characteristics are analyzed, including yield strength, ultimate tensile strength, and elongation at high temperatures. The findings reveal that both steels experience changes in mechanical behavior at elevated temperatures, with decreased strength and increased ductility. S1100 steel demonstrates improved high-temperature mechanical qualities compared to S960 steel. The study provides valuable insights for selecting the appropriate steel in high-temperature environments, ensuring the reliability of engineering. These findings hold utmost significance in the context of selecting the most appropriate steel for applications in high-temperature environments, thereby ensuring the reliability and performance of engineering systems. By shedding light on the specific mechanical responses of S960 and S1100 steels to elevated temperatures, this study offers valuable insights that can inform decision-making processes across diverse industries, facilitating the optimal selection of materials for applications subject to high-temperature conditions. Consequently, this research contributes to advancing the understanding of steel behavior under thermal stress and supports the development of more robust and efficient engineering solutions.

SYMBOLS AND ABBREVIATIONS

Roman characters

F	force	[N]
T	temperature	[ºC]
z	transition strain	[MPa]

Greek characters

ε	Strain	
σ_S	saturation stress	
σ	Stress	[MPa]

Constants

k	empirical constant	[MPa]
n	strain hardening exponent	

Abbreviations

BMs	Basic Material(s)
CEV	Carbon Equivalent
DP	dual phase
HSLA	high-strength low-alloy
UCM	Unified Constitutive Model
UHSS	ultra-high-strength steel
SEM	scanning electron microscope

TMCP	thermo-mechanical controlled process
TEM	transmission electron microscopy

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1 Introduction

The remarkable mechanical qualities of ultra-high-strength steels, which include high strength and superior ductility, make them perfect for usage in a variety of industrial applications. Yet, much like any material, their characteristics are susceptible to alteration under certain circumstances.

Work hardening, which happens when a material is deformed under stress, is one of the major processes that affect the characteristics of ultra-high strength steels. Work hardening, which can lead to better mechanical characteristics, is defined by an increase in the material's strength and hardness as a result of the deformation.

The temperature at which ultra-high-strength steels are produced has a significant impact on the degree of work hardening. Higher degrees of work hardening are produced as a result of the material being more pliable and simpler to deform at high temperatures. Nevertheless, the material becomes more brittle at lower temperatures, making it harder to deform and producing less work hardening.

The development of robust, long-lasting, and affordable buildings has been a trend in the metal building construction industry. As a result, the usage of ultra-high-strength steels has expanded. These steels have outstanding mechanical properties that enable the use of lighter and thinner components without compromising strength or durability. The quality of material required to withstand the stresses induced at critical spots in a metal construction can be decreased by selecting stronger materials that can be linked properly. This results in lighter, more effective structures that are also simpler and less expensive to build. Also, using stronger metals can aid in lowering the quantity of welding material needed to fill a bevel. This lowers the negative effects of welding on the environment and saves time and money. Also, the use of lighter and thinner materials in metal structures lowers the quantity of raw materials required for production, which might lessen the total environmental effect.

In conclusion, stronger, lighter, more affordable, and more ecologically friendly metal structures have been made possible by the invention of ultra-high-strength steels. These materials are a key element in the movement toward effective and sustainable building methods.

It is crucial to comprehend how temperature and work hardening interact with ultra-high-strength steels in order to optimize these materials' mechanical characteristics for various uses. This information may be used to direct the choice of processing parameters and aid in the creation of novel materials with improved qualities.

To assess work hardening and the behavior of steel, material scientists frequently employ the Hollomon model, a mathematical equation. This model offers a mathematical explanation of how stress and strain interact during plastic deformation. The Hollomon model enables scientists and engineers to anticipate and comprehend the mechanical reaction of steel under various loading circumstances by include material factors like the strain hardening exponent and the initial flow stress. In industries where the mechanical characteristics of steel are critical for design and performance concerns, the model's ability to quantify work hardening the increase in material strength and resistance to deformation is particularly helpful. For its adaptability and efficiency in forecasting material behavior under varied stress situations, the Hollomon model is well-known. The interactions between stress, strain, and temperature are precisely captured by its robust formulation, which is supported by substantial study and validation. The Hollomon model is a highly regarded and frequently used option in engineering applications, despite the potential superiority of alternatives models like the Osgood model in particular situations. These models also acknowledge the broad applicability, extensive validation, and comprehensive understanding of material behavior.

1.1 Objectives, research problem, research questions and limitations

This thesis aims to understand the mechanism of strain hardening and its impact on the mechanical properties of materials, while developing predictive models for strain-hardening behavior. The process of strain hardening is intricate and impacted by several variables. A multidisciplinary approach combining materials science, mechanical engineering, and physics is necessary for a thorough understanding.

S960MC is an ultra-high-strength steel that is frequently employed in the mechanical engineering and automotive sectors. It has been treated at elevated temperatures and pressures to produce its high-strength qualities since it is a thermomechanical rolled steel. Work hardening is a procedure that puts stress on a material to make it stronger and harder.

When a material is under stress, its atoms transforms, making it tougher and more durable. In this regards, work hardening is a procedure that is frequently used to strengthen the strength of materials like steel. S960MC steel has the ability to be work-hardened and is suitable for structural and cold-forming applications. The adoption of suitable heat treatment techniques is essential to maintaining the intended qualities of the material since work hardening may also make the material more brittle. For the automotive industry specifically, ultra-high-strength steel (UHSS) known as S1100 was developed. A few of the several microstructures that make up this intricate, multi-phase steel are martensite, bainite, and retained austenite. This confluence of microstructures accounts for the exceptional strength and toughness properties of S1100.

When a material is under stress, its atoms changes, resulting in a harder, more resilient substance. To increase the tensile strength of materials like steel, the process of "work hardening" is routinely employed. Despite the fact that S1100 steel is already quite strong and hard, it may be made even stronger by applying stress to the material by cold working or stamping. This knowledge is essential for creating materials with particular thermal characteristics and may be used to guide the development of new materials for a variety of applications. Researchers may improve their knowledge of how materials behave under certain heat circumstances and spur innovation in the field of material science by using cutting-edge testing techniques and measuring tools. S1100 is a brand-new high strength steel that was developed specifically for the automobile industry and combines high strength with exceptional formability. It may be used to create cross members, reinforcements, and crash-relevant components, among other structural elements.

It is difficult to create realistic models to predict the strain-hardening behaviour of materials since the behaviour is impacted by a variety of variables and can vary depending on the material and circumstances. However, the development of more complex models that might assist us in better understanding and predicting the strain-hardening behaviour of materials has been made feasible by advancements in computational methods and the accessibility of vast quantities of data.

1.1 Framework

The framework employed in this study Table 1, revolves around investigating the influence of temperature on the work hardening behavior of ultra-high-strength steels. The primary focus is to understand how variations in service temperature affect the mechanical response of these materials during plastic deformation. The main variable of interest is the service temperature, which represents the temperature at which the steel is subjected to mechanical loading or operational conditions. The objective is to analyze the changes in strain-hardening parameters, specifically the coefficients in Hollomon's equation, as indicators of the material's work-hardening behavior. Hollomon's equation, a widely accepted empirical equation, relates the true stress to the true strain during plastic deformation. By quantifying the temperature-dependent alterations in these coefficients, this framework aims to uncover the intricate relationship between temperature and the work hardening response of ultra-high-strength steels. The findings from this research have the potential to provide valuable insights for industries utilizing these materials and contribute to the broader field of materials science.

In Figure 1, the direction of the experimental and scientific investigation is depicted, taking into account the sequential steps involved in this study. The process commences with an extensive literature review, followed by the collection of relevant data. Subsequently, tensile tests are conducted on specimens to generate experimental data. The collected data is then meticulously analyzed, the primary objective is to concentrate on the factors linked to the tests, with the intention of adapting the Hollomon model using the engineering data and subsequently assessing and providing justification for this model.

Table 1. Frame work ralaed to the project of the master thesis

Scope	Variable	Influence	Type of influence
influence of temperature on the work hardening behavior of ultra-high-strength steels	service temperature of the material	strain hardening behavior	changes in strain-hardening parameters, i.e., Hollomon's coefficients

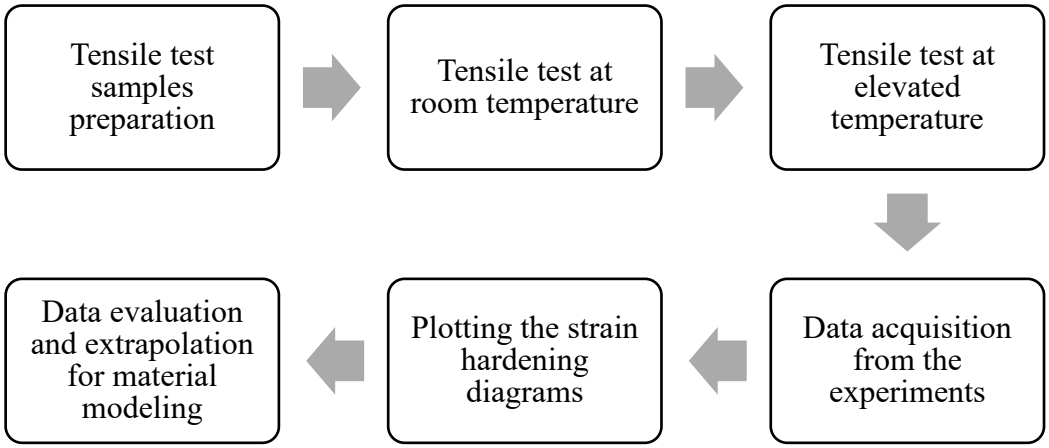

Figure 1. Big picture of things that will be done in this thesis related to the frame work

Research questions:

- What is the impact of temperature on the strain hardening behavior of Ultra-high-strength steels (UHSS)? The objective is to investigate how varying temperature conditions influence the material's ability to undergo plastic deformation and enhance its strength through work hardening.

- To what extent is the Hollomon equation accurate in evaluating the strain-hardening behavior of UHSS at different temperatures? This question aims to assess the validity and precision of the widely-used Hollomon equation as a predictive model for quantifying the strain hardening response of UHSS across a range of temperature environments.
- How do the Hollomon parameters evolve in response to different deformation temperatures? This question focuses on examining the changes in the strain-hardening coefficients and Hollomon's constant, fundamental parameters in the Hollomon equation, as a result of varying deformation temperatures. By elucidating these temperature-dependent variations, the study aims to enhance the understanding of UHSS's strain hardening behavior.

By addressing these research questions, the study seeks to contribute to the existing knowledge on the influence of temperature on UHSS's strain hardening behavior and assess the accuracy of the Hollomon equation as a predictive tool. These insights hold potential implications for material design and optimization in practical applications where UHSS is exposed to diverse temperature conditions.

2 Literature review

Steel structure assembly, manufacture, and construction have traditionally been associated with high resource consumption, It is anticipated that more than 80% of steel will be recycled successfully as a result of the adoption of strong steel recycling activities, significantly reducing the need for additional raw iron resources. When compared to the current situation, where the emission rate is 1.6 tons of CO2 for 1 ton of steel, the adoption of fossil-free techniques in steel manufacturing is projected to deliver a notable reduction in CO2 emissions, resulting in near-zero levels. To address these concerns, there has been a growing interest in exploring alternative construction materials, such as lightweight composites, which compete with steel due to their affordability and environmental advantages. However, the demand for defensive armor with exceptional strength and durability has prompted extensive research in the field of ultra-high-strength steels (UHSS). These materials, often composed of thin plates and incorporating various alloying additives, offer superior mechanical properties and are widely used in applications requiring high strength-to-weight ratios. To evaluate and optimize the performance of UHSS, experimental tensile testing plays a crucial role. Tensile tests involve subjecting UHSS specimens to controlled levels of axial tension until failure, allowing researchers to understand the material's mechanical behavior, including its yield strength, ultimate tensile strength, and ductility. In recent years, the Hollomon model has emerged as a valuable tool for analyzing the stress-strain behavior of UHSS during tensile testing. The Hollomon equation relates the true stress (σ) and true strain (ε) experienced by the material, taking into account the strain hardening effect. By fitting experimental data to the Hollomon equation, researchers can determine material-specific parameters, such as the strain hardening exponent (n) and the strength coefficient (K), which provide insights into the material's deformation characteristics.

Through the experimental tensile test of UHSS and subsequent analysis using the Hollomon model, researchers aim to gain a deeper understanding of the material's mechanical properties, its response to various loading conditions, and its suitability for specific engineering applications. This research not only contributes to the advancement of UHSS technology but also enables the development of more efficient production techniques and optimization strategies to enhance the material's characteristics, performance, and service life. have also emphasized the importance of conventional approaches, which involve

alloying additions, adequate heat treatment, and improved production techniques, in enhancing the properties and performance of UHSS. These approaches, combined with experimental testing and analytical modeling, contribute to a comprehensive evaluation of UHSS materials and their potential in diverse engineering applications (Siddique & Li & Yin. 2022).

2.1 Steel and its application in construction and structures

Metal structures require steel since it is a key engineering material. Several industries, including working machines, car industries, transportation, shipbuilding, and construction, rely significantly on this resource. These resource-intensive businesses are today more concerned with effectively preserving the environment and promoting sustainable growth as a result of the current natural disaster brought on by climate change and high carbon emissions. Natural resources must be used more effectively, energy use and carbon emissions must be cut, and material waste must be kept to a minimum if these objectives are to be met. (Afkhami & Javaheri& Amraei. 2022, p. 213.)

Due to its good weldability and high ductility, high-strength low-alloyed (HSLA) structural steel is one of the most appealing building materials. Structures with significant material volume requirements to support design loads, such as cranes, long-span beams, and drill string components, among others, are immediate examples where metal weight is equivalent to external loads. These industries, which heavily rely on steel, are increasingly prioritizing environmental preservation and sustainable growth due to the current impact of climate change and high carbon emissions. To meet these objectives, it is imperative to enhance the efficient utilization of natural resources, reduce energy consumption and carbon emissions, and minimize material waste. Furthermore, high-strength low-alloyed (HSLA) structural steel emerges as an appealing construction materials due to its favorable weldability and high ductility. Notably, structures with substantial material volume requirements, including cranes, long-span beams, and drill string components, exemplify cases where the weight of metal correlates with the external loads needed for proper support (Steimbreger & Gubeljak & Vuherer. 2022, p.2).

Material scientists have always been interested in designing and creating metallic materials and alloy systems with higher mechanical qualities, improved performance, and longer service lives. Steel competes with lightweight composite constructions as well owing to its affordability. As a result, thin plates made of ultra-high-strength steels with various alloying additives are frequently utilized as protective armor, and much research is still being done in these fields. the traditional approaches of achieving improvements in prop Steel is an alloy made up of iron and other elements, primarily carbon. Steel can be produced in different grades, each with unique properties and intended uses. It is also highly recyclable, making it a sustainable material for many industries. (Vafaeian & Fattah-alhosseini & Mazaheri. 2016, p.488)

Over the past several decades, steels with varying degrees of strength have been employed in a variety of applications, including the global skyscraper and bridge-building business, the automotive sector, and big-span bridge construction. development of high and ultra-high-strength steels (HSS/UHSS) has been prompted by trends toward lessening the exploitation of natural resources and conserving energy in recent years, on the one hand, and by consumer demand for rapidly advancing technology, on the other. The excellent load-bearing capacity, high strength-to-weight ratio, and superior weldability of these materials make them extremely beneficial in a wide range of industrial applications (Ghafouri & Amraei & Pokka. 2022a, p. 2).

These reviews conclude that, Steel possesses desirable mechanical qualities, improved performance, and extended service life, making it a preferred choice for metallic materials and alloy systems. Its affordability and competition with lightweight composite constructions further solidify its position. Steel's applications range from construction and transportation to manufacturing, with the ability to produce different grades tailored for specific properties and uses. Additionally, steels recyclability adds to its sustainability in multiple industries. The advancements in high and ultra-high-strength steels (HSS/UHSS) have been driven by the need to conserve natural resources and energy while meeting consumer demands for technological advancements. These steels offer exceptional load-bearing capacity, high strength-to-weight ratio, and superior weldability, making them highly beneficial for various industrial applications, including global skyscraper and bridge construction, the automotive sector, and big-span bridge construction. Consequently, the

paragraphs emphasize the ongoing research and development efforts in these fields to enhance steel's mechanical qualities and explore its potential in protective armor and other areas.

2.2 Ultra-high-strength steels

The term "ultra-high-strength steel" (UHSS) refers to a type of steel known for its exceptional ability to withstand high strains without cracking or breaking. This is due to its unique microstructure, characterized by a high density of extremely small grains. UHSS finds extensive use in industries such as automotive, aerospace, and military, where both its high strength and ductility are highly valued. Achieving the desired microstructure and properties of UHSS often involves specific processing methods, including extreme plastic deformation.

High-strength steels are in high demand due to their superior mechanical properties, offering strength, hardness, and formability. These steels are commonly used in various applications, such as mobile cranes, axle and chassis components, and lifting equipment. The exceptional strength of these steels allows for reduced weight in the final product, leading to lower fuel consumption and CO2 emissions. (Mičian & Winczek & Harmaniak. 2021, p. 81)

Roll forming is a widely used method for processing UHSS. It enables the production of straight components with complex cross sections by gradually bending the sheet through a set of rollers, rather than deforming a blank through stretching and drawing. The complexity of the component's cross-sectional geometry determines the number of required supports for the rollers, typically ranging up to 35 stands. Roll forming offers energy efficiency as it distorts only a small area of the blank compared to stamping operations. Although roll forming has been less common in automotive applications due to its limitation to straight geometries, recent advancements in computing power and numerical control have led to the popularity of flexible roll forming for processing automobile structures (Hazra et al 2017).

Roll forming, a widely employed method for processing ultra-high-strength steels (UHSS), enables the production of straight components with complex cross sections through a gradual bending process. While roll forming has historically been limited to straight geometries, recent advancements in computing power and numerical control have popularized flexible

roll forming for processing automobile structures. This method offers energy efficiency by distorting only a small area of the blank compared to stamping operations.

A significant challenge in the field of structural steel research is the toughening of ultra-high-strength low-alloy steel with a yield strength of 1.4 GPa or higher. Providing complex-shaped components and members with defined mechanical characteristics poses an additional challenge. This limitation hampers the full realization of the technical potential and application of ultra-high-strength low-alloy steels. Thermomechanical steel treatments, such as heated temp forming, involve extreme plastic deformation of ultra-high-strength tempered martensitic steels at elevated temperatures (500–700°C) and are commonly employed to address these challenges (Kimura & Inoue. 2020)

Engine downsizing has led to smaller engines with increased mechanical and thermal demands on their internal components. Consequently, high-strength engine fasteners must possess the ability to resist creep at high temperatures while maintaining a high yield strength under such conditions (Ohlund & Lukovic & Weidow. 2016, p. 1875).

Ultra-high-strength steel (UHSS) with its unique microstructure and exceptional mechanical properties plays a vital role in industries such as automotive, aerospace, and military. Processing methods like roll forming and thermomechanical treatments have been employed to shape UHSS components and enhance their performance. Overcoming challenges related to toughening and achieving defined mechanical characteristics in ultra-high-strength low-alloy steels remains an active area of research. Additionally, in the context of engine downsizing, high-strength engine fasteners are essential to withstand increased mechanical and thermal demands.

2.2.1 S960MC

The use of many strengthening mechanisms in one process is possible when steel is produced using a thermo-mechanical controlled process (TMCP). For S960MC steel and other comparable grades of high-strength steel, the most frequent strengthening processes are grain boundary strengthening, dislocation strengthening, and precipitation strengthening. (Mičian et al., 2022)

By substituting high-strength steel S960MC for regular mill steels (S355), construction can achieve weight reductions of up to 60%. Another compelling argument in support of using high-strength steel in the production (including design and fabrication) of transportation vehicles is that doing so would help reduce air pollution since lighter cars will use less fuel and have less of an impact on the environment. (Jambor & Novy & Mician. 2018, p. 31)

Even when cutting-edge techniques are employed, such as the micro-jet cooling method, and when various welding wires are utilized, the S960MC steel is particularly challenging to weld since the mechanical qualities of the weld can be reduced by 50%. (Szymczak & Szczucka-Lasota & Węgrzyn. 2022)

Table 2, provides a summary of the studied S960MC base material's chemical composition in accordance with the material certificate.

Table 2. Chemical composition of the investigated S960MC steel (Mičian et al. 2021).

Chemical composition (wt.%)											
C	Si	Mn	P	S	Al	Nb	V	Ti	Cr	Ni	Mo
0.09	0.18	1.06	0.01	0.003	0.036	0.002	0.007	0.03	1.08	0.07	0.1

2.2.2 S1100

After welding, S1100's microstructure showed no hazardous phases in the base metal or along its HAZs, with the exception of a few trace quantities of tempered martensite. The islands of tempered martensite, despite their size and distribution, were not large enough to have an adverse impact on the static mechanical characteristics of the welded joints. (Afkhami et al. 2019, p. 15890)

Certain welded UHSS grades appear to suffer from a hardness drop, however, this may be prevented by delaying ferrite formation in these steels. Similar to S1100, this goal may be accomplished by altering the chemical composition and early microstructure of steel through changes in the steel-making process. (Afkhami et al. 2022)

At the ICHAZ, the S960 showed a 29% reduction in the magnitude of its Vickers hardness, whilst the S1100 only showed a maximum reduction of 4%. Furthermore, at their HAZs, the

two sheets of steel exhibited distinct softening/hardening behaviors. The softened HAZ (Heat Affected Zone) caused the S960 to lose a significant amount of its hardness, which was consistent with earlier accounts. Specimens 1-4 represent the hardening behavior that the S1100 alloy exhibited at its HAZ. The weld thermal cycle No. 4 had the highest measured hardness, which was 13% greater than the S1100 BM. A similar hardening trend is documented at the HAZ of S1100.(Amraei & Afkhami & Javaheri et al. 2020a)

The quenching and tempering procedure was used to create the S1100 grade. Hot rolled strips that were 8 mm thick provided the steel alloy. Table 2 lists the chemical compositions (in weight percentages) of the steel S1100 grades in accordance with the manufacturer's certifications.

In table 3, carbon equivalent (*CEV*) was computed for S1100 and S960 using the following equation. The calculation of *CEV* shown that the S1100 carbon equivalant is more than S960. (Ghafouri & Amraei & Pokka et al. 2022b)

$$CEV = \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (1)$$

Table 3. The nominal chemical composition of BMs S1100 and S960 (Ghafouri et al. 2022)

	Chemical composition (wt.%)										
Material	*C*	*Si*	*Mn*	*P*	*S*	*V*	*Cu*	*Cr*	*Ni*	*Mo*	*CEV*
S1100	0.129	0.18	1.48	0.006	0.002	--	0.439	1.29	0.9	0.371	0.83
S960	0.097	0.20	1.09	0.008	0.001	--	0.033	1.13	0.3	0.191	0.3

2.2.3 Importance of strain hardening in steel

A crucial step in the manufacture of steel, strain hardening, sometimes referred to as work hardening or cold working, includes the material's plastic deformation under mechanical stress. The steel becomes stronger and harder as a result of this process, increasing its resistance to deformation and failure under stress. The following are some of the main advantages and uses of strain hardening in steel: (Zhang et al. 2019)

1. Strain hardening may greatly enhance the steel's strength and toughness, making it more resistant to fatigue, fracture, and typically it reduces the plastic deformation capacity. This is crucial in structural applications where the steel needs to be strong enough to sustain heavy loads and strains.

2. Strain hardening may increase a steel's ductility, or its capacity to flex without breaking, in addition to hardening and strengthening it. The occurrence of strain hardening is observed during the deformation process, leading us closer to the ultimate fracture point.

3. Cost savings: Strain hardening may be utilized to create components made of high-strength steel that are more lightweight and thinner than conventional designs, which can save manufacturing and material costs. In addition, by decreasing wear and corrosion, it can increase the service life of components.

4. Versatility: Strain hardening is a versatile procedure for enhancing the performance of numerous components and structures. It may be used to a broad variety of steel

alloys. It may be used to a variety of projects, including infrastructure and the automobile and aerospace industries.

Strain hardening is an important step in the manufacturing of steel that can increase the material's strength, toughness, and ductility. It is an invaluable tool for a variety of technical and industrial applications thanks to its advantages, which include greater durability, cost savings, and adaptability (Zhang & Xue & Cui. 2019, p. 4250)

Throughout the early 1970s until recently, the two most significant design elements employed in automotive manufacturing facilities have been improving safety and reducing vehicle weight. New steels with enhanced formability, high strength, and advantageous strain-hardening indices have been developed to handle this challenging task. The end result of this intensive research effort is to develop lightweight cars that can withstand serious crashes while keeping passengers safe. More contemporary high-strength steels are being used in the vehicle sector. (Bassini & Sivo & Ugues. 2021)

Being a crucial characteristic of metals and other materials, strain hardening is frequently studied using equations that express the interaction between strain and stress. A variety of models have been put out to describe the complicated behaviour of materials under strain and to forecast their mechanical characteristics under various circumstances (Jia & Hao & Luo. 2022, p. 2077)

The Ramberg-Osgood equation, which expresses the stress-strain relationship in terms of two parameters the elastic modulus and the strain-hardening coefficient—is one of the earliest and most basic models of strain hardening. It has been demonstrated that this equation provides a good match for various metals and has been widely utilized in the technical community for a range of purposes. (Ha, Lee & Barlat. 2013)

The Portevin-Le Chatelier effect, which describes the intermittent and jerky deformation behavior of some materials under strain, is one of the more sophisticated models for strain hardening that have been presented. To account for the effects of temperature, strain rate, and other variables on strain hardening behavior, additional models have been created (Ha et al. 2013)

Continuum mechanics principles may be used to describe the microscale deformation of materials as a way to predict strain hardening. For instance, crystal plasticity models may depict how individual crystals interact during the deformation of metals and how grain size,

texture, and other microstructural elements affect strain-hardening behavior.(Hartmaier et al. 2020)

Another strategy is to create empirical models of strain-hardening behaviour using data-driven methodologies. Artificial neural networks, for example, have been used to represent the intricate link between strain, stress, and other elements in materials and can make precise predictions under a variety of circumstances. (Hartmaier et al. 2020)

In general, there is a substantial and expanding body of literature on strain-hardening models and equations, highlighting the significance of this trait for a variety of engineering and scientific applications. The complicated behaviour of materials under strain continues to be studied by researchers, who are also working to create new techniques for predicting the mechanical characteristics of materials under various situations. (Hartmaier et al. 2020; Jia et al. 2022; Zhang et al. 2019)

Researchers have so far put out a number of hypotheses to explain strain events. To encourage innovation and give a more accurate description of material deformation behavior, these initial constitutive models might be updated, simplified, or improved. Although it is still a work in progress, the investigation of numerical solutions in conjunction with analytical methods has achieved significant advancements. These approaches offer the capacity to theoretically forecast the design and assessment of material and structural performance under high-speed impacts, taking into account the quick absorption of considerable energy within fractions of seconds throughout the deformation process. Numerical solutions and constitutive equations must be used to effectively visualize the nonlinear mechanical behavior of materials subjected to dynamic loads. (Siddique et al. 2022.)

There have been several attempts to use constitutive equations to describe the behavior of metals during strain-hardening. For this job, the Crussard-Jaoul and Hollomon formulations are primarily used. These models are renowned for simulating the n and K indices of the genuine strain-true stress curves. In general, if severe plastic deformation is required, a material with a high value of n is chosen. Also, a high value of n shows that the material has a greater rate of strain hardening, which allows It to resist significant deformation before becoming unstable. (Bassini et al. 2021)

2.2.4 Hollomon

The connection between true stress and true strain during the plastic deformation of a material is described by the empirical Hollomon equation. Predicting how metals and alloys will behave under tensile stress is commonly employed in the field of materials science and engineering. John Hollomon created the equation in the 1940s, and it has since grown into a crucial tool for comprehending the mechanical characteristics of materials (Rukwied & Ballard et al. 1972. p. 3001).

In mathematical terms, the Hollomon equation is:

$$\sigma = K\varepsilon\text{^}n \tag{2}$$

Where σ (sigma) is the true stress, ε (epsilon) is the true strain, K is strain hardening coefficient and n is strain hardening exponent (in some K_H and n_H are used as Hollomon constant) that depend on the material under study and are the real stresses and strains, respectively. The rate at which the material hardens during plastic deformation is indicated by the exponent n, sometimes referred to as the strain-hardening exponent.(Rukwied & Ballard. 1972)

A number of researchers have studied the applicability of the Hollomon equation in predicting the mechanical characteristics of materials. The Hollomon equation, for instance, was shown to be able to precisely predict the stress-strain behavior of low-carbon steel at varied strain rates and temperatures in research by (Micallef & Fallah & Pope. 2012). The Hollomon equation was also utilized in research by et al (Shariq 2019) to simulate the stress-strain behavior of a nickel-based superalloy at high temperatures. They discovered that the equation offered an excellent match to the experimental data.

Several academics have looked into how the Hollomon equation might be used to forecast how materials would fail. For instance, (Raju et al .2017) utilized the equation to simulate the tensile behavior of a copper-based shape memory alloy and discovered that it could precisely forecast when necking would start to occur and when failure would occur. The

Hollomon equation has also been utilized in the creation of constitutive models for modelling the behavior of materials under various loading circumstances, in addition to its utility in predicting the mechanical characteristics of materials. For instance, (Wang & Shen & Maggi . 2018) utilized the equation to create a constitutive model for high-strength steel under dynamic loading circumstances and discovered that the model could successfully forecast the material's deformation behavior.

The Hollomon equation has been widely applied in the fields of materials science and engineering and is a potent tool for predicting the mechanical characteristics of materials. It is a crucial equation for comprehending the behavior of metals and alloys during plastic deformation due to its simplicity and adaptability.

2.2.5 Modified Hollomon

Understanding the mechanical behavior of materials is crucial for developing and producing components and structures in materials science and engineering. A well-liked empirical model for describing the strain-hardening behavior of materials is the Modified Hollomon equation. An overview of the Modified Hollomon equation and its use with diverse materials is given in this study of the literature.

The original Hollomon equation was modified by Stuwe and Hutchinson in 1978 by adding a factor to account for the saturation of strain hardening at high strains. A common method for expressing the flow stress of materials during plastic deformation is the resultant Modified Hollomon equation. The Modified Hollomon equation was expanded by Yue and Jonas in 1997 to take temperature, strain rate, and strain into consideration when calculating the flow stress of materials. The Unified Constitutive Model (UCM), a version of this model, is currently widely used to forecast how materials will behave when subjected to heated deformation. (Stuwe & Hutchinson 1978; Finnie 1977.)

Metals, polymers, and ceramics are just a few of the materials to which the Modified Hollomon equation has been used. Meyers and Chawla (2008) emphasize the significance of precisely defining the strain-hardening behavior of materials in order to anticipate their mechanical response under different loading circumstances. They emphasize how the

Modified Hollomon equation may be used to simulate the behavior of various materials. (Meyers & Chawla 2008.)

Wang et al. (2020) use the Modified Hollomon equation to explore the strain-hardening behavior of the 5A06 aluminium alloy. They discover that the strain-hardening parameters change dramatically as the strain increases, pointing up the necessity of precisely describing the strain-hardening behavior of materials for correct mechanical response modelling.

In summary, simulating the behavior of materials during strain-hardening has shown to be a valuable use of the Modified Hollomon equation. More precise predictions of material behavior under diverse loading circumstances are now possible because to its numerous improvements and additions. To make accurate predictions, it is crucial to precisely define the behavior of particular materials, as with any empirical model. Many materials have been subjected to the Modified Hollomon equation, which has demonstrated significant promise for future advancement in the study of materials science and engineering.

2.2.6 Voce

A phenomenological model that represents the plastic deformation behavior of metals is the Voce equation. In metal forming operations including rolling, forging, and extrusion, it is frequently used to assess and forecast the flow stress. Since Voce's initial introduction of the equation in 1955, it has undergone substantial study and uses in the field of materials science and engineering.

The Voce equation and its use in various metal-forming processes have been studied by several researchers. For instance, Balasubramanian (Balasubramanian & Ramakrishnan & Narayanasamy. 2015) modeled the flow behaviour of aluminium alloy A5083 during hot deformation using the Voce equation. They discovered that the equation correctly predicted the material's flow stress and strain rate behavior under various deformation scenarios.

Based on the Voce equation (Choudhary et al. 2001.)

$$\sigma = \sigma_s - (\sigma_s - \sigma_1) - exp(n_V \varepsilon) \quad (3)$$

where σ_S is the saturation stress, σ_I is the true stress and n_V constant

A different research, (Chang & Lee 2018) used the Voce equation to examine how the deformation temperature affected the flow characteristics of the magnesium alloy AZ31. They saw that the equation could be used to forecast how the material would flow under various temperature conditions, which was crucial for improving the metal-forming process.

Several further research has concentrated on enhancing the precision and application of the Voce equation. For instance, (Wang & Wang & Lu et al. 2019) provided a modified form of the Voce equation that considered the impact of titanium alloy grain size on flow stress. They discovered that compared to the original Voce equation, the updated equation offered a superior match to experimental data.

Accordingly, the Voce equation is a common model for estimating metals' flow stress during plastic deformation. Several experts in the field of materials science and engineering have thoroughly investigated and enhanced its accuracy and application.

2.2.7 Ludwigson

A statistical model called Ludwigson is employed in the study of hydrology to determine a river's design flood. Since Ludwigson originally proposed it in 1963, it has been extensively utilized in hydrological engineering and design. The model, which is used to determine the magnitude and likelihood of floods that are expected to occur in a specific time period, is based on the idea of the frequency analysis of severe events.

Ludwigson equation:

$$\sigma = K_1\varepsilon^{n_1} + exp\,(K_2+n_2\varepsilon) \quad (4)$$

where K_1 and n_1 are the same as k and n in the Hollomon equation (equation 2), respectively, and K_2 and n_2 are additional constants. (Choudhary et al. 2001)

Several academics have looked at the use and precision of the Ludwigson model in various hydrological scenarios. (Bonilla Valverde, Blank, Roidt, *et al.* 2016), for instance, compared the Ludwigson model's performance with that of other frequently employed statistical models for determining the design flood for a river in China. They discovered that the Ludwigson model produced the most precise estimations, making it the best model for their research domain.

In a different investigation, (Kjeldsen, Bacon & Smithers 2014) assessed how well the Ludwigson model performed in determining the design flood for a river in the UK. They discovered that the model could predict the design flood for the study area with accuracy and indicated that it may be used to comparable situations in other areas.

Improvements to the Ludwigson model's precision and dependability have also been the subject of several additional research. (Mei & Li 2016, p. 810), for instance, offering a modified version of the model that took into account how climate change affects the frequency and severity of floods. They discovered that in areas where climate change is anticipated to have an impact, the adjusted model generated estimates of the design flood that were more precise.

In conclusion, the Ludwigson statistical model is a popular tool in hydrology for determining a river's design flood. Several academics in the field of hydrological engineering and design have investigated and improved upon its accuracy and applicability in great detail.

2.2.8 Ludwik model

Based on the Ludwik equation. (Ludwik 1909.)

$$\sigma=\sigma_0+K\varepsilon^n \tag{5}$$

The mechanical behavior of materials, particularly in the plastic deformation zone, is described mathematically by the Ludwik model. Below is a concise assessment of some of the influential articles on the Ludwik model. In a tensile test, Ludwik developed an empirical

link between the genuine stress and strain that may be represented by a power law with an exponent below one (Ludwik 1909.)

Et al (Holomonski 1976) analysis of tensile test results using the Ludwik equation. According to Holomonski, the equation may be used to fit stress-strain data for a variety of materials, and he also offers a technique for figuring out the equation's parameters. Et al (Kim, Kim & Lee 2003), the mechanical behavior of a zirconium-niobium alloy is examined using the Ludwik model. The Ludwik equation is used by the authors to fit stress-strain data from tensile testing, and finite element analysis is used to examine how different strain rates affect the alloy's mechanical behavior.

The mechanical behavior of concrete that has been changed with polymers is studied in this work using a modified version of the Ludwik model. The nonlinear stress-strain behavior of the material at high strains is taken into consideration by the authors by modifying the Ludwik equation. Experimental results from tensile testing on the concrete are demonstrated to be well fit by the modified model (Ma Guo & Xie 2019.)

In these mentioned studies et al (Kim, Kim & Lee 2003) and (Ma et al. 2019), the little investigation and use of substitute models or equations for the Ludwik equation in fitting stress-strain data in materials. There has been little research into alternative equations or models that would offer a better fit or a more accurate depiction of the mechanical behavior of various materials, despite the fact that the Ludwik equation is stated as a way to fit stress-strain data in all the aforementioned papers. This points to a need for study into and evaluation of other equations or models that, beyond the Ludwik equation, can accurately describe the stress-strain connection in varied materials. We might better understand material behavior and produce more precise forecasts and assessments across a range of industries and applications by investigating and contrasting alternative modeling methodologies.

2.2.9 Swift model

The Swift model is a mathematical representation of the strain-hardening behavior of materials under deformation used in materials science and engineering. The process by

which a material grows stronger and harder when it is deformed is known as strain hardening, often referred to as work hardening or cold working.

Based on swift equation (6):

$$\varepsilon=\varepsilon_0+k'\sigma^n \quad (6)$$

The Swift (6) model is predicated on the idea that the rate of hardening and the rate of plastic strain are inversely related. In other words, a substance grows harder the more it is distorted. The connection between stress (σ) and strain ε during deformation is described by the model using a single parameter, the strain hardening exponent (n). The Swift model is a popular tool in the fields of materials science and engineering because it helps to understand and anticipate how materials will behave when they are deformed.

3 Experimental procedure

Examining the mechanical characteristics of ultra-high strength steels at high temperatures was the main goal of this investigation. An extensive program of tensile testing was done to achieve this. The experiments were carried out at a range of increased temperatures, from 20°C to 900°C. These tests were conducted using a particular testing tool, which is shown in Figure 8. Two distinct heating chambers were part of this device, which could support a maximum load of 100 kN. An experimental temperature range of 300°C to 1200°C was possible in one of the heating chambers, which was a three-zone resistance heating furnace. About 20°C per minute was how quickly the furnace heated up. Three N-type thermocouples were installed on the top, middle, and bottom of the specimen in this chamber to monitor the sample's temperature. An environmental chamber was used at temperatures below 300 °C. A K-type thermocouple was positioned on the top or lower portion of the sample in this chamber in order to precisely monitor the temperature. Contact-type extensometers were used during the tensile testing to detect strain. A "makroXtens" extensometer by Zwick with expanded arms was utilized in the environmental room. A high-temperature MayTec extensometer with ceramic sensor arms was used for the three-zone resistance furnace. Room temperature (RT), 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, and 900°C were the seven goal temperatures that the study concentrated on. The sample was securely placed within the chamber and heated to the target temperature during the course of the test at a consistent rate of 20°C per minute. In order to remove any thermal gradients and guarantee a consistent temperature distribution, the sample was then maintained at the desired temperature for 5 minutes. Up until the sample ruptured, strain-controlled tensile tests were performed at a constant strain rate of 0.0001 S(-1). The testing process adhered to recognized methods that have been previously reported in literature reviews , notably those that were carried out at Oulu University (Ghafouri, et al. 2022b).

S960 and S1100 steel samples with gauge lengths of 35 mm and cross-sectional areas of 25 mm x 8 mm are procured to start the experiment. The tensile tests are carried out using a piece of universal testing equipment outfitted with a high-temperature furnace that can reach up to 1200°C. The testing apparatus is calibrated in accordance with the manufacturer's instructions prior to the tests, and the precision of the displacement and load sensors is confirmed. The testing facility is kept at room temperature, and the testing machine's

crosshead speed is adjusted at a constant 1 mm/min. After the specimen is in the testing device's grips, axial tensile pressure is given to it until it breaks. Each specimen's tensile strength, yield strength, and elongation at fracture are determined, and the load-displacement curve is documented. Tensile strength, yield strength, and elongation at fracture are measured from the load-displacement curve for each specimen. The findings for each type of steel at various temperatures are then compared, and it is established how temperature affects the mechanical characteristics of ultra-high-strength steels S960 and S1100.

3.1 Sample preparation

S960MC and S1100 steels with low carbon levels were the basic materials (BMs) taken into consideration for this investigation. Whereas the S1100 grade was produced using the quenching and tempering method, the as-received S960MC was produced using contemporary hot rolling and direct quenching techniques. Both steel alloys came from hot rolled strips that were 8 mm thick. The manufacturer's certifications specify the chemical compositions (wt%) of the two steel grades in Tabale.1 and 2. (Amraei, Afkhami, Javaheri, *et al.* 2020b; Siltanen, Tihinen & Kömi 2015)

Table 5, presents valuable experimental data related to the mechanical properties of the tested samples under different conditions. The results highlight the influence of temperature and loading rate on the material's behavior and performance. Firstly, the variation in temperature reveals its significant impact on the mechanical properties of the samples. As observed in the table, different temperature levels yield different yield strengths, ultimate tensile strengths, and elongation values. This suggests that temperature plays a crucial role in altering the material's response to applied loads or strains. Understanding this temperature dependency is essential for designing and engineering materials to withstand specific operating conditions. Secondly, the loading rate employed during the experiments influences the mechanical properties of the samples. As indicated in the table, varying loading rates result in different yield strengths, ultimate tensile strengths, and elongation values. This suggests that the rate at which loads or strains are applied affects the material's ability to withstand deformation and resist failure. The loading rate sensitivity demonstrated by the samples emphasizes the importance of considering the loading conditions when designing structures or components. Figure 2, is a drawing of the used specimen in this study. All S960

and S1100 specimens are In the same shape as shown in Figure 3, with same angles and standards.

Table 4. Nominal mechanical properties of the parent materials (Ghafouri et al 2022c).

Steel	Min 0.2% proof strength (MPa)	Ultimate tensile strength (MPa)	Elongation A5 (%)
S960	1028	1126	9
S1100	1126	1153	11

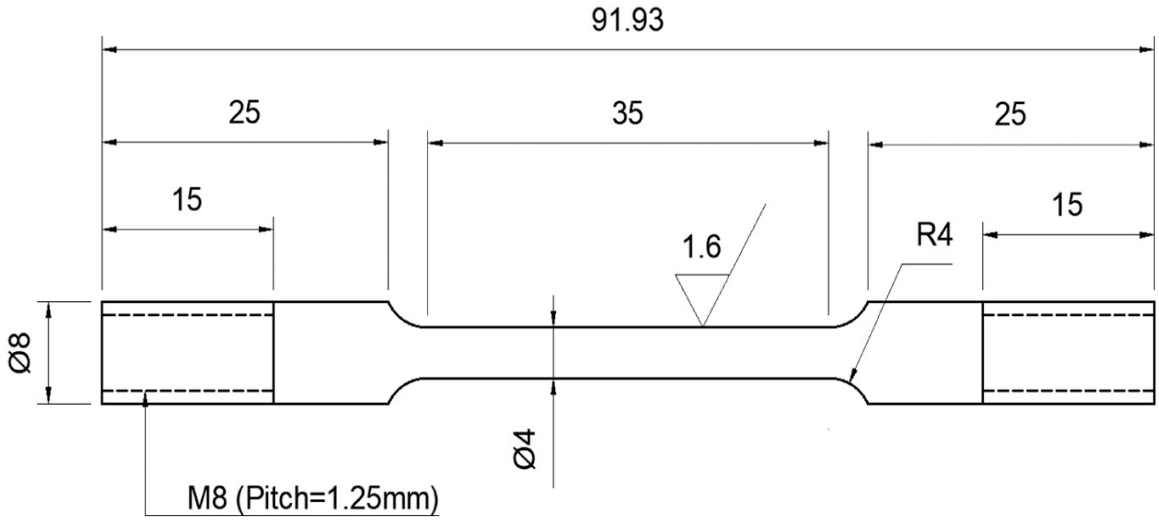

Figure 2. schematic drawing of the specimen which is used in this experimental study (the dimensions are in mm)

3.2 Tensile tests

A common technique for assessing the mechanical characteristics of materials, particularly ultra-high-strength steels (UHSS) like S960 and S1100, is tensile testing. A method for analyzing the behavior of materials under high-temperature circumstances is elevated-temperature tensile testing.

Tensile testing at elevated temperatures can provide crucial details regarding the mechanical characteristics of UHSS, including as their tensile strength, ductility, and resistance to

deformation at high temperatures. The outcomes of these experiments can be used to guide the design and creation of UHSS for high-temperature applications.

According to studies, UHSS like S960 and S1100 display special mechanical characteristics at high temperatures that can be very different from those of the material at ambient temperature. For instance, UHSS materials may show decreased strength, greater ductility, and higher susceptibility to deformation at high temperatures.

The UHSS sample is initially placed in a heating chamber that may be heated to 1300°C to perform a tensile test at elevated temperatures. A specialized testing device is then used to apply a tensile force to the sample while continually monitoring the temperature and strain. Researchers may learn more about the mechanical characteristics of UHSS such as S960 and S1100 in high-temperature circumstances by examining the results of enhanced temperature tensile tests. The design of UHSS for high-temperature applications, such as those in the aerospace and automotive sectors, may be optimized using this knowledge.

To investigate the behavior of materials under heat settings, several steady-state (isothermal) hot tensile experiments were carried out (figure 3). The experiments were conducted utilizing the Zwick/Roell Z100 testing apparatus, which has two different heating chambers and a maximum load capacity of 100 kN. The materials were tested in a three-zone resistance heating furnace, commonly known as a high-temperature furnace, at temperatures between 300 and 1300 degrees Celsius (figure 4,5). Three N-type thermocouples were firmly fastened to the upper, middle, and bottom sections of the material under test in the testing apparatus. This made it easier to keep track of the temperature within the heating chamber continuously and allowed for perfect temperature control during the test. The samples were heated at a pace of 25 degrees Celsius (℃) per minute (figure 3), which made sure that the process was regulated and reliable. Overall, by using this cutting-edge testing apparatus and exact temperature monitoring system, it was possible to get accurate and trustworthy information on the tensile characteristics of various materials under varied heat settings. The outcomes of these experiments are essential for improving our comprehension of how materials behave in high-temperature environments and may be used to guide the development of new materials for a variety of applications.

Figure 3. Room Temperature (25℃) sample tensile test

In figure 4, the process of the elevating temperature for over 100℃ is shown. there are termocoupls and fixtures which are fixed by the specimen in the tensile test system.

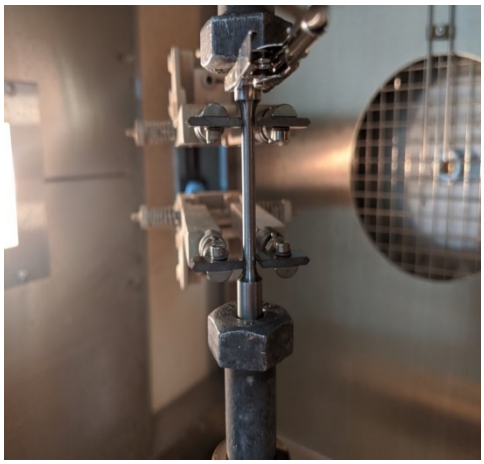

Figure 4. Tensile test 300 ℃ temperature

For temperatures below 300 ℃ (figure 5), an environmental chamber was utilized. One K-type thermocouple linked to the specimen's top or lower portion was used to measure the temperature in this chamber.

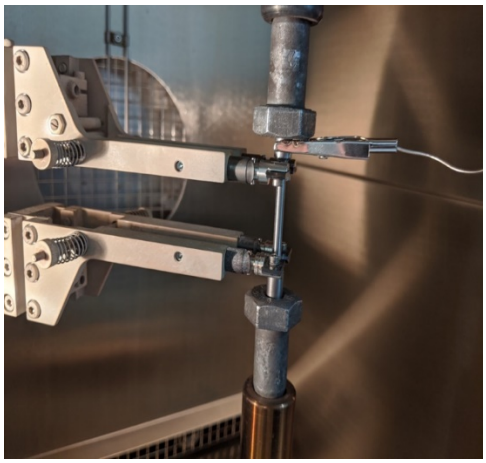

Figure 5. Tensile test in 500℃

Using contact-type extensometers, the strain on the specimen was precisely measured during the tensile testing procedure. In the environmental chamber, a high-temperature MayTec extensometer with ceramic sensor arms was used, and in the three-zone resistance furnace, a "makroXtens" extensometer with extended arms was used (figure 6). Throughout the testing procedure, these cutting-edge measuring instruments made accurate and dependable data collecting possible. Room temperature (RT), 100°C, 200°C, 300°C, 400°C, 600°C, 700°C, 800°C, and 900°C were the seven target temperatures that the testing was done. The samples were precisely placed into the testing chamber, held there, and heated there at a consistent rate of 20°C per minute until the appropriate temperature was reached. The samples were kept at the desired temperature for five minutes prior to loading to guarantee a constant and uniform temperature. The accurate measurement of strain and the gathering of trustworthy data at each target temperature were made possible by the use of these sophisticated extensometers and exact temperature control techniques.

Figure 6. tensile test up to 1200 ℃ (900℃)

The provided figures, specifically figures 4, 5, and 6, serve to present a comprehensive summary of the experimental procedure employed during the tensile test. These images offer a depiction of the manner in which the specimens were secured and the subsequent alterations in temperature that transpired throughout the duration of the tests. Notably, the experimental protocol remained consistent for both specimen materials. However, a key distinction arose in the utilization of thermocouples, which varied in correspondence with the elevated temperatures employed. In the initial stages of the experiment, encompassing ambient conditions such as room temperature, the implementation of specialized thermocouples was deemed unnecessary. Nonetheless, as the experiment progressed and the temperature was incrementally increased, the installation of thermocouples became imperative. These thermocouples were employed to accurately monitor and record the changing temperatures experienced by the specimens. Overall, these images provide a visual representation of the experimental procedure undertaken during the tensile test, elucidating the manner in which the specimens were affixed and the corresponding temperature variations that transpired. The distinction in thermocouple usage, which was contingent upon the specific elevated temperatures, emerges as the primary divergence between the experimental conditions for the two specimen materials.

4 Mathematical calculations

The strain-hardening behavior of the specimens was analyzed using the Hollomon power law relation. Excel was employed to implement this model equation. Initially, all engineering data, divided into engineering strain and engineering stress, were examined for each temperature. Subsequently, true data were computed using mathematical formulation to obtain true stress and true strain data. Microsoft Excel work sheet features utilized to insert data into the figures of engineering stress-strain, resulting in the generation of graphical representations. Both data of engineering and true conditions were combined into a single figure to evaluate the shape of the steel's behavior. Using these analytical techniques achieved a thorough understanding of the specimen's strain-hardening behavior.

$$linear = \left(\frac{\sigma}{E}\right) + 0.002 \tag{7}$$

$$\Delta = linear - \varepsilon \tag{8}$$

where σ is engineering stress [MPa], ε is engineering strain, E is tangent modulus [MPa]

$$\varepsilon_0 = ln(\varepsilon + 1) \tag{9}$$

where ε_0 is true strain and ε is engineering strain.

$$\sigma_0 = \sigma * (\varepsilon + 1) \tag{10}$$

where σ_0 is true stress [MPa], ε is engineering strain.

The term "*linear*" refers to selecting the linear portion of the stress-strain curve and constructing a linear plot, which yields a line equation that incorporates the tangent modulus in units of megapascals (MPa). By utilizing equation (7) to determine this feature for each stress-strain point, we can establish the "linear" component. This feature serves to demarcate the ultimate stress point and identify regions where the strain is negative. Once the "linear" component has been identified, it can be utilized to calculate the delta element in equation (8). This calculation enables us to pinpoint the ultimate stress point (σ_0)in the test results. After identifying the maximum stress point, The corresponding yield strength can be established. Subsequently, the true stress-strain data in the plastic zone will be taken into account, which is served as a crucial input for continuing the subsequent calculations. For definition of true stress-strain equations (9,10) are used.

Following the completion of the aforementioned calculation steps, the data necessary for evaluating the Hollomon equation is obtained. To utilize the Hollomon equation effectively, it is imperative to establish the values of two empirical constants, namely k and n, which are integral components of the equation. Once these values are determined, the Hollomon equation can be fully defined, enabling the construction of the Hollomon figure. Subsequently, the Plastic Stress-Strain figure must be plotted to assess its congruence with the model and derive conclusive outcomes. In order to ascertain the values of K and n in Equation (2), the logarithmic natural (ln) curve of the plastic stress-strain relationship needs to be plotted. Subsequently, the equation of the linear segment of the curve facilitates the determination of n, while the exponential function of k is derived. This comprehensive procedure allows for the finalization of the results and the establishment of a robust understanding of the material's behavior.

5 Results and discussion

As a result of plastic deformation under room temperature, a process known as strain hardening, often referred to as work hardening or cold working, develops in metals and alloys. This procedure makes the material stronger and harder by forcing dislocations, or faults in the crystal structure, to accumulate and interact with one another, making it harder for them to move and increasing the material's strength. The ability to dramatically improve metals' strength and toughness without the use of heat treatment or other expensive procedures is one of the key advantages of strain hardening. Because of this, it is a desirable alternative for many technical and industrial applications, including the creation of structural components for buildings and bridges as well as in the aerospace and automobile sectors.

Strain hardening, however, might potentially have certain drawbacks. For starters, it can make the substance more brittle and prone to breaking, which might be a problem in situations where the substance is put under a lot of stress or is being hit by weights. The procedure may also result in a loss of ductility, which might make the material more challenging to form or shape. The degree of strain hardening that is applied to the material should also be considered. The phenomenon of material deformation is accompanied by a series of effects that build up to failure. The material first gradually loses its ability to deform as it goes through deformation. The material's reduced capacity for plastic deformation without fracture denotes a restriction on its structural integrity. The material may then suffer the beginning and spread of cracks as the deformation continues. These fractures reflect limited areas of damage and act as precursors to more severe failure modes. They are frequently begun at locations of high stress concentration or material flaws. If the cracking persists, it may eventually result in total failure, when the material is unable to support the imposed load and suffers a catastrophic collapse. To guarantee that the material has the appropriate qualities and performance characteristics, it is crucial to precisely manage the amount of strain hardening that is performed throughout the production process. Work hardening is an effective tool for enhancing the strength and toughness of metals and alloys, but it needs to be carefully controlled to prevent potential downsides and guarantee that the material functions as intended in practical applications. Engineers and manufacturers may choose when and how to employ this process to produce the results they want by knowing its workings and constraints.

5.1 S960MC

The stress-strain curve acquired during the test may be used to examine the work-hardening behavior of S960MC steel during a tensile test. When a material is deformed under strain, it becomes stronger and harder, a process known as "work hardening." With a yield strength of 960 MPa, S960MC steel is a high-strength low-alloy (HSLA) steel. The stress-strain curve exhibits a linear connection between stress and strain throughout the early phases of the tensile test, which is referred to as the elastic area. When the stress is released at this point, the material recovers to its former shape; no lasting deformation has occurred. The stress-strain curve reaches the plastic area as the load rises, causing the material to irreversibly deform. With increased plastic deformation, the work-hardening behavior of S960MC steel is characterized by a notable rise in strength and hardness. The dislocations in the material's microstructure interact with one another and entangle when it deforms, obstructing their mobility and making the material stronger and harder. As a result, the stress-strain curve in the plastic zone has a steeper slope, suggesting that additional stress is needed to further distort the material. The material eventually reaches its ultimate tensile strength (UTS), which is the highest engineering stress it can endure prior to breaking. Indicating that the material is undergoing necking, a confined deformation when the cross-sectional area of the material drastically reduces, the engineering stress-strain curve starts to level out and may even show a tiny reduction at this point. When the material finally breaks, the test is over. In a tensile test, S960 steel exhibits work-hardening behavior that is characterized by a notable rise in strength and hardness along with rising plastic deformation. This phenomenon results from interactions between dislocations in the microstructure of the material, which get twisted and restrict their mobility when the material is deformed. The test is concluded when the material finally reaches its UTS and cracks.

5.1.1 Tensile test results and strain-hardening graphs of S960MC

The engineering graphs in figures 7 and figure 8, depict the behavior of steel specimens at varying temperatures. Commencing at room temperature, a tensile test was conducted, and data were gathered under various loads. Subsequently, utilizing the mathematical formulae outlined in the thesis, the true stress-strain curve was determined and illustrated on the same

graphs to highlight the differences observed at each temperature. The test was initiated at room temperature and was carried out up to 900 ℃. The curves show the data till the ultimate strength point. According to the figures data of Table 5, which are included tangent modulus, ultimate stress, yield strength, and uniform elongation are defined and collected for each temperature. Notable deviations have been observed in the values of the tangent modulus Tabale 5, yield strength, and ultimate strength of S960MC specimens during the controlled elevation of temperature in the tensile testing process. These parameters are meticulously collected and subjected to rigorous analysis to effectively evaluate the testing procedure's efficacy. Specifically, the tangent modulus values have decreased from 202204 MPa at room temperature to 11008 MPa at 800℃ and then increased to 181604 MPa at 900℃. Although the testing process indicates a consistent reduction in tangent modulus, a detailed and precise evaluation reveals a significant decrease up to 800℃, followed by an increase up to 900℃. The observed decrease in tangent modulus can be attributed to several factors. Firstly, the increase in temperature may cause thermal expansion of the material, resulting in a decrease in the stiffness of the material due to an increase in the distance between atoms. Secondly, elevated temperatures can activate the material's thermal defects, such as dislocations or vacancies, leading to imperfections and a decrease in the material's strength. Thirdly, phase transformations, such as melting or recrystallization, may significantly alter the material's microstructure and mechanical properties at high temperatures.

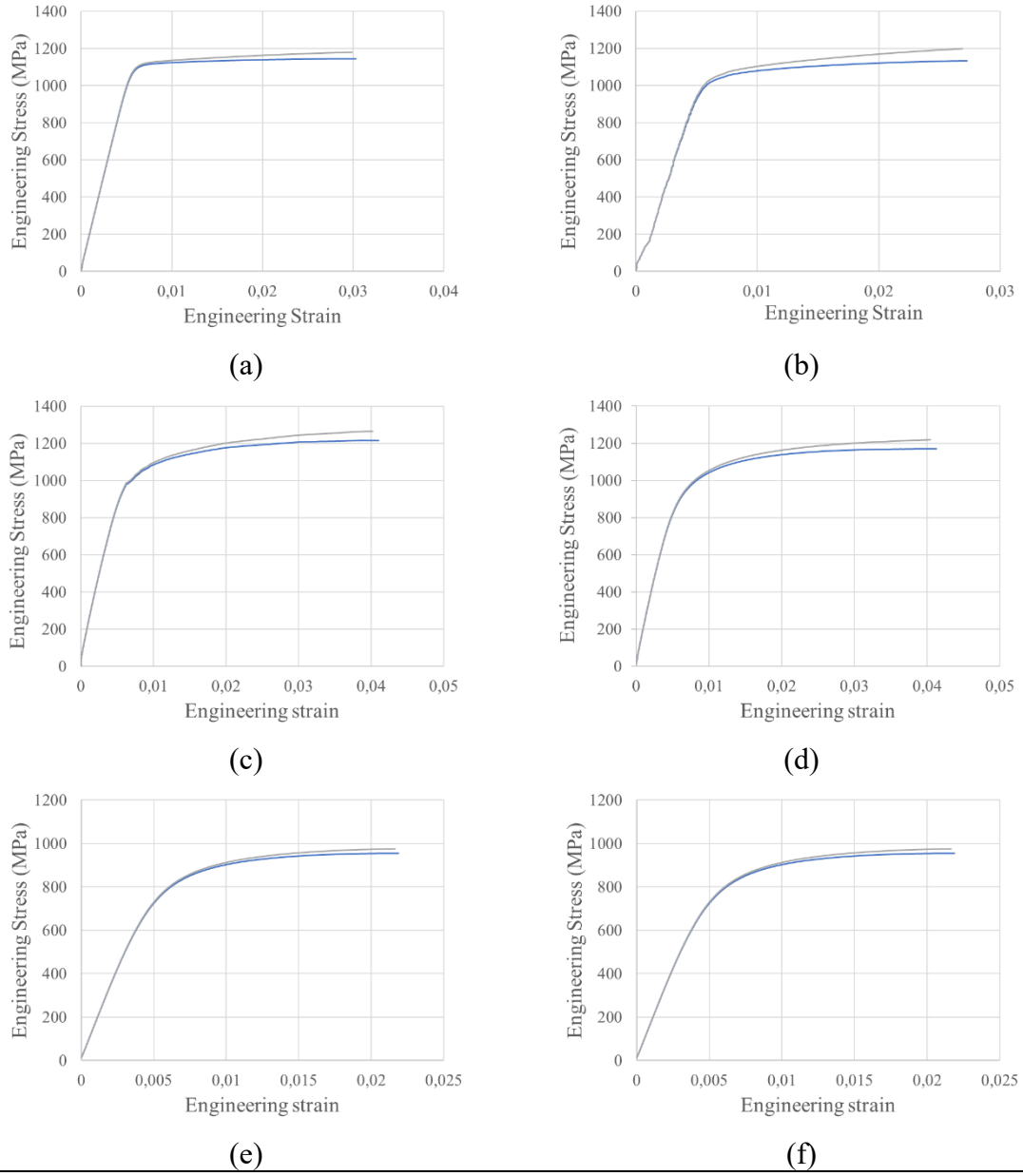

Figure 7. Stress-Strain graphs for S960 in elevated temperature tensile test results. comparision of true data and engineering data from the test. [Graphs from (a to f) are shown temperatures (RT(25℃), 100℃, 200℃, 300℃]

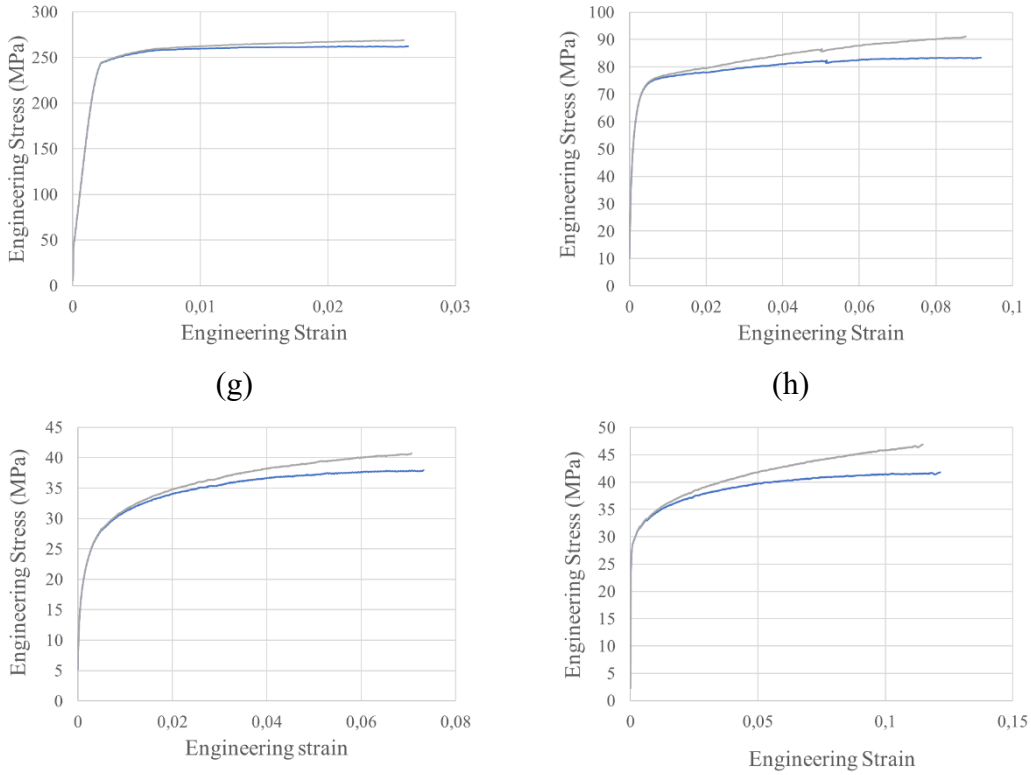

Figure 8. Stress-Strain graphs for S960 in elevated temperature tensile test results. comparision true data and engineering data from the test. [Graphs from (g to j) are shown temperatures (600℃, 700℃, 800℃, 900 ℃)]

The reduction in the tangent modulus observed in S960MC specimens during the tensile testing process at high temperatures reveals a complex phenomenon influenced by multiple variables. One of the factors contributing to this reduction is thermal expansion, which occurs as the temperature rises. As the material is exposed to higher temperatures, its atomic vibrations increase, leading to an expansion of the crystal lattice. This thermal expansion causes a decrease in the tangent modulus, which quantifies the mater'al's stiffness and ability to resist deformation. In addition to thermal expansion, the presence of thermal defects can also contribute to the observed reduction in the tangent modulus. At elevated temperatures, defects such as dislocations, vacancies, or impurities within the material become more mobile. The increased mobility of these defects facilitates their movement and interaction, leading to a disruption in the crystal structure and subsequent decrease in the tangent modulus. These defects act as sources of stress concentration, promoting localized deformation and reducing the overall stiffness of the material.

Furthermore, phase transformations play a significant role in the observed reduction of the tangent modulus at high temperatures (table 6). Many materials, including S960MC, undergo phase changes as the temperature increases. These transformations involve the rearrangement of atoms and changes in the crystal structure, which can significantly affect the mechanical properties of the material. The occurrence of phase transformations during tensile testing at high temperatures introduces additional complexities in the mater'al's behavior, leading to a decrease in the tangent modulus. It is important to note that the reduction in the tangent modulus (tabale 6) is not solely attributed to any single factor but is the result of the combined influence of thermal expansion, thermal defects, and phase transformations. The interplay between these variables complicates the understanding and prediction of the mater'al's response under high-temperature conditions. Further research and experimental investigations are necessary to gain a more comprehensive understanding of the specific mechanisms driving the observed reduction in the tangent modulus and to develop accurate models to predict material behavior in such conditions. By comprehending the factors affecting the reduction in the tangent modulus at high temperatures, researchers, engineers, and material scientists can make informed decisions in the design and selection of materials for applications involving elevated temperature environments. This understanding drives improved materials and strategies to mitigate high-temperat're's impact on mechanical performance.

Table 5. Mechanical properties S960MC during tensile test in elevated temperatures

S960	Tengent modulus (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform elongation
RT	202204	1115	1144	0,0298
100 C	183928	1057	1134	0,0268
200 C	184465	1020	1215	0,0402
300 C	178973	970	1171	0,0404
400 C	159574	843	954	0,0216
500 C	141245	633	671	0,0217
600 C	122395	251	262	0,0259
700 C	84458	68	83	0,0877
800 C	11008	27	38	0,0706
900 C	181604	30	41	0,1147

Upon the conclusion of all calculations and reporting of results, a crucial subsequent step involves guiding the Hollomon fitting process by establishing the natural logarithm (ln) for both the true plastic strain and stress. This step is vital in accurately determining the Hollomon parameters, namely the strain hardening exponent (*n)* and the strength coefficient (*K).* To facilitate this analysis, graphical representations are constructed to visualize the LN curves. By utilizing the natural logaritem transformation, the true plastic strain and stress values are logarithmically scaled, enabling a more meaningful interpretation of the relationship between these variables. The ln curves, graphically represented, exhibit distinct patterns that provide valuable insights into the materials deformation behavior and its response to applied loads. These graphical representations are essential for identifying the Hollomon parameters, as they allow for a clear visualization of the trend and characteristics of the ln curves.

The natural logaritem (ln) curves serve as a visual guide for the determination of the Hollomon parameters. The strain hardening exponent (*n*) is obtained from the slope of the ln curve of the true plastic strain, representing the mater’al's ability to resist further deformation as plastic strain increases. Meanwhile, the strength coefficient (*k*) is derived from the intercept of the (ln) curve of the true stress, reflecting the mater’al's initial strength

or yield stress. Accurately identifying these parameters through graphical analysis is crucial for obtaining reliable and comprehensive insights into the material's mechanical behavior.

These LN curves figure (table 9 and table 10) and subsequent analysis aid in the understanding and characterization of the materials deformation mechanisms and its ability to withstand applied loads. The extracted Hollomon parameters provide valuable information for engineering design and material selection, facilitating the prediction and optimization of material performance in various applications.

The inclusion of natural logarithm curves in the Hollomon fitting process plays a pivotal role in accurately determining the strain hardening exponent *(n)* and strength coefficient (*k*). Through graphical representation and analysis, these curves provide crucial visual insights into the material's deformation behavior. Consequently, this information contributes to a comprehensive understanding of the material's mechanical response, aiding in engineering design considerations and optimizing material performance.

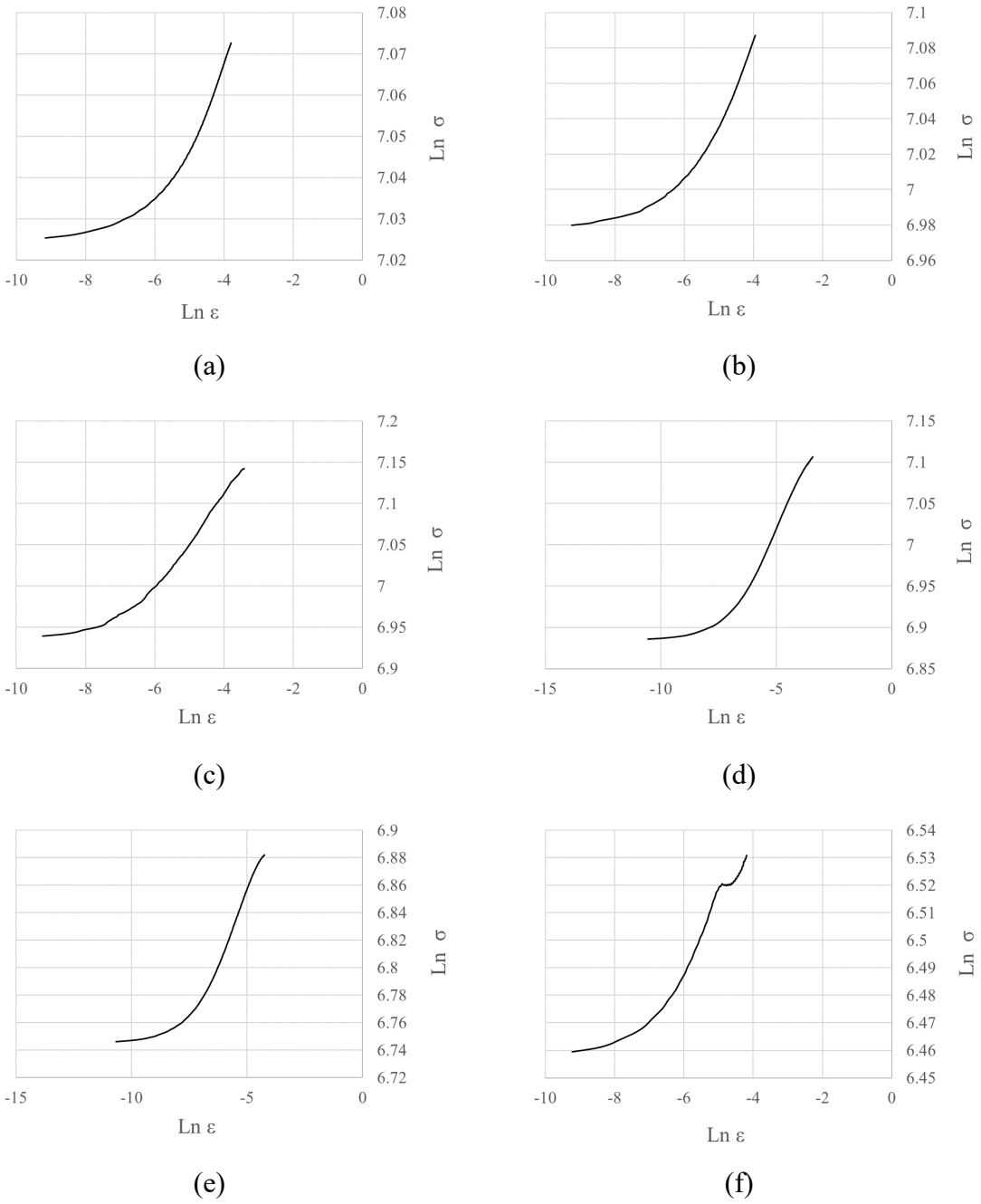

Figure 9. ln curves of epsilon (ε) and sigma (σ) for S960 Specimens in tensile test to calculate the n and k from the line equation and put in the Hollomon model. [Graphs from (a to f) are shown temperatures (RT (25 °C) , 100°C, 200°C, 300°C, 400°C, 500°C]

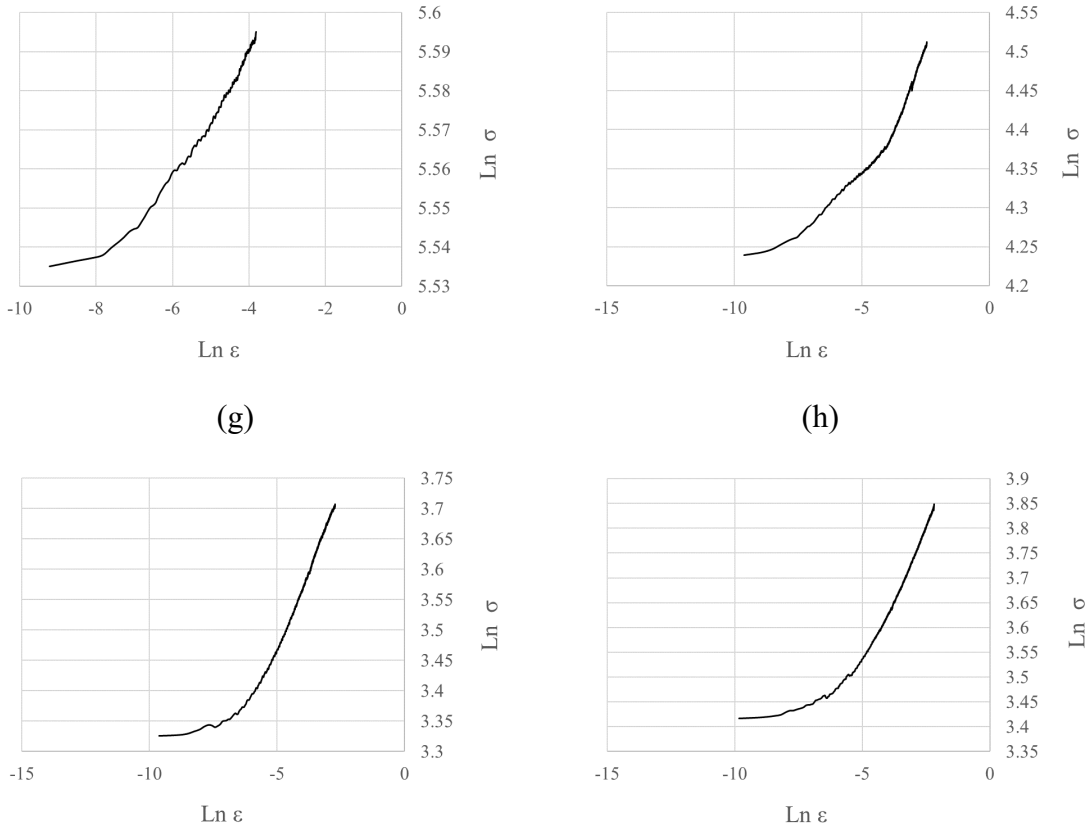

Figure 10. ln curves of epsilon (ε) and sigma (σ) for S960 Specimens in tensile test to calculate the n and k from the line equation and put in the Hollomon model. [Graphs from (g to j) are shown temperatures (600℃, 700℃, 800℃, and 900 ℃)]

After careful examination of Figure 11 and 12, we have conducted a thorough analysis of the data pertaining to the Hollomon equation (2). The relevant data has been meticulously compiled and consolidated in Table 6, specifically focusing on the S960 material. The inclusion of this table serves the purpose of enhancing our comprehension and facilitating a more comprehensive understanding of the key parameters [*n, K, R^2*] associated with the Hollomon equation

Through careful extraction and organization of the pertinent data from these figures13a and 13b, Table 6 has been constructed to provide a consolidated overview of the essential parameters for the Hollomon equation. Specifically, the table includes the strain hardening exponent (*n*), the strength coefficient (*K*), and the coefficient of determination (*R^2*) for the S960 material. The strain hardening exponent (*n*) characterizes the ability of the material to

resist further deformation as plastic strain increases, while the strength coefficient (*k*) represents the initial strength or yield stress. Additionally, the coefficient of determination (*R^2*) serves as an indicator of the goodness-of-fit between the experimental data and the Hollomon equation model, offering insights into the accuracy and reliability of the equatinss predictions for the S960 material.

The incorporation of table 7, with its concise presentation of the relevant parameters (*n, k, R^2*), significantly contributes to a more precise understanding of the S960 material's mechanical behavior and its response to applied loads. This comprehensive data analysis fosters informed decision-making processes in engineering design, material selection, and performance prediction for a wide range of applications involving the S960 material. The careful analysis of Figures 13a and 13b has yielded crucial insights into the S960 materials behavior in relation to the Hollomon equation (2). The resultant data has been thoughtfully compiled and presented in Table 6, allowing for a thorough examination of the key parameters [*n, k, R^2*]. The inclusion of this table facilitates a deeper understanding of the S960 materials deformation characteristics, enabling more informed decision-making and enhancing the overall knowledge base in the field of materials science and engineering.

Table 6. [*n, k, R^2*] related to the Ln curve for S960 tensile test

S960	RT°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C
n	0,0128	0,0281	0,0498	0,0494	0,0328	0,194	0,0144	0,0547	0,0888	0,0927
k	1230	1319	1494	1443	1117	742	283	101	51	55
R^2	0,8734	0,8866	0,9647	0,9623	0,9388	0,9465	0,9654	0,9176	0,9548	0,9423

5.1.2 Extrapolations and equations fittings of S960MC

The Hollomon equation (2) must be used after figuring out the values of n and K for each unique load. In figure 14a and 14b, The Hollomon curves is generated using the equation, and the model is assessed by superimposing it on the actual plastic stress-strain curve. According to the fitting result, the model is correct at some temperatures but not advised at others, as seen in the following data. After 200°C, the model is useful, and it fits the data well at 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, and 900°C.

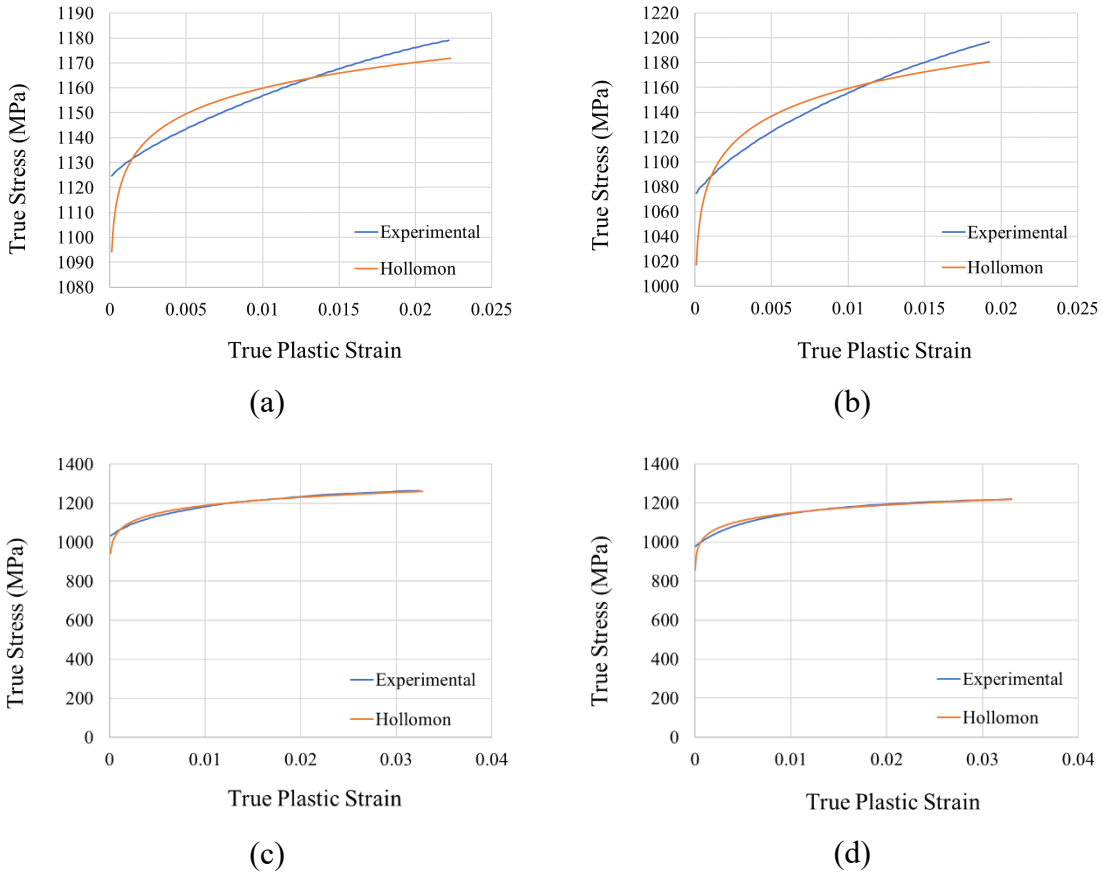

Figure 11. Fitting Hollomon model and true plastic stress-strain curve for S960MC specimens in the tensile test in elevated temperatures [(a)to (d)are remain the temperatures, RT(25 ℃), 100℃, 200℃, 300℃]

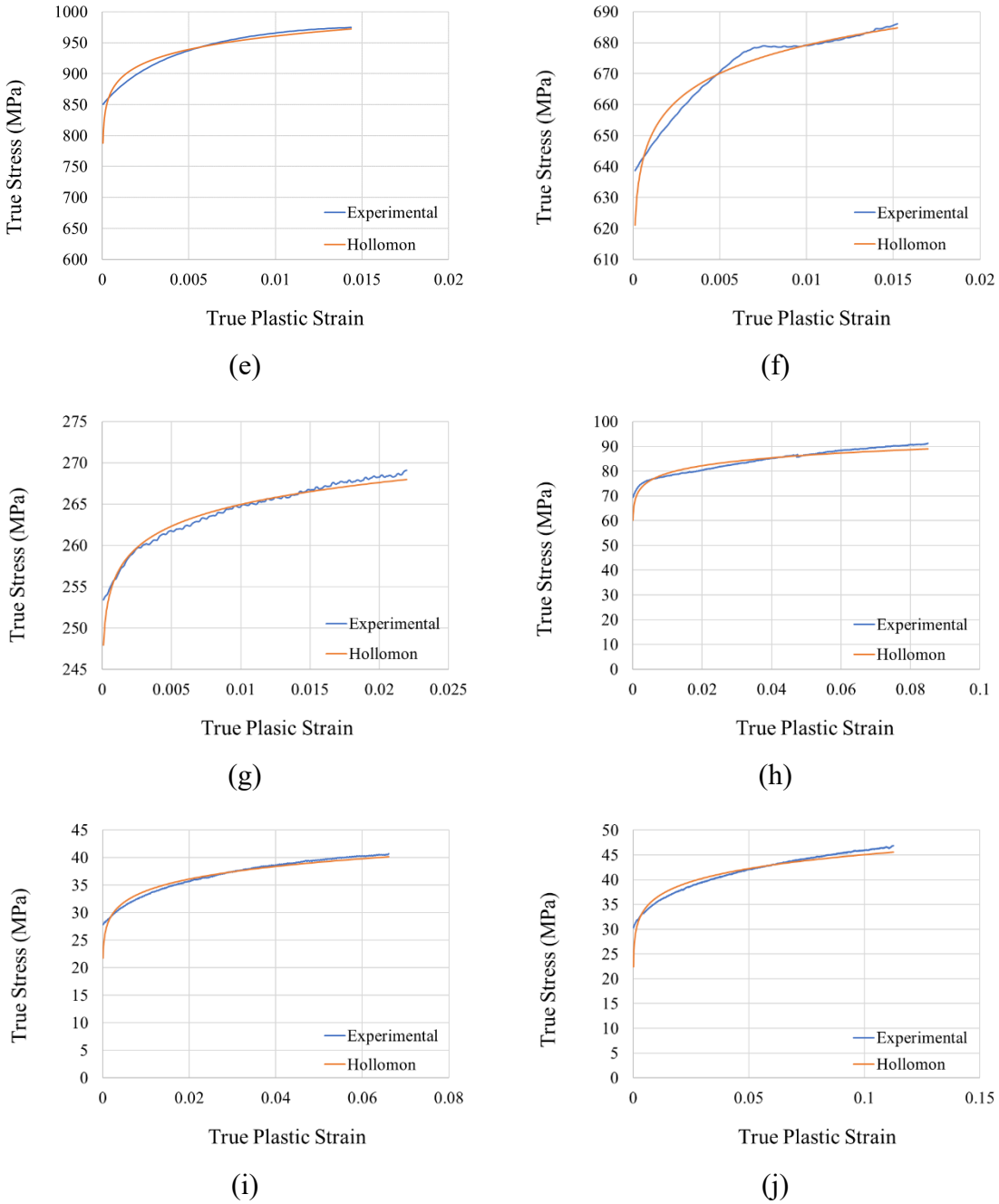

Figure 12. Fitting hollomon model and true plastic stress-strain curve for S960MC specimens in the tensile test in elevated temperatures [(a)to (f)are remain the temperatures 400℃, 500℃, 600℃, 700℃, 800℃, 900℃]

5.2 S1100

S1100 is a specific type of ultra-high-strength steel (UHSS) that possesses exceptional mechanical properties and is widely utilized in various industries. It is characterized by its high strength, excellent toughness, and superior resistance to deformation. The composition of S1100 is carefully engineered to achieve a balance between strength and ductility, making it suitable for applications where both strength and impact resistance are critical. The unique microstructure of S1100, typically consisting of fine-grained martensite and other strengthening phases, contributes to its remarkable mechanical performance. This steel grade has gained significant attention due to its potential for lightweight construction, enabling the development of lighter and more energy-efficient structures without compromising safety and durability. Research efforts focused on S1100 aim to further understand its mechanical behavior, optimize its processing parameters, and explore its potential applications in industries such as automotive, aerospace, and structural engineering.

5.2.1 Tensile test results and strain-hardening graphs S1100

Figure 13 and figure 14, findings of the tensile test performed on S1100 specimens at high temperatures show in the results section. The tests objectives were to assess the material's mechanical characteristics at various temperatures and to see how it reacted to tensile stress. In order to determine important material properties like flow stress, strain hardening, and strain rate sensitivity, mathematical models are used to assess the experimental data that was gathered during the test and are given in graphical and tabular form. The st’dy's findings offer information on S1100 st’el's potential for use in high-temperature applications, and they might be a useful tool for scientists and engineers working in the field of materials science and engineering. Overall, the combination of experimental and mathematical methods provided a comprehensive understanding of the material properties of S1100 steel under tensile loading conditions, enabling the researchers to evaluate the efficacy of the Hollomon model in predicting its behavior in elevated temperatures.

By examining the trends and patterns observed in the data, researchers can gain a better understanding of how S1100 steel behaves under tensile loading at high temperatures, and how it may perform in real-world applications where high-temperature resistance is critical.

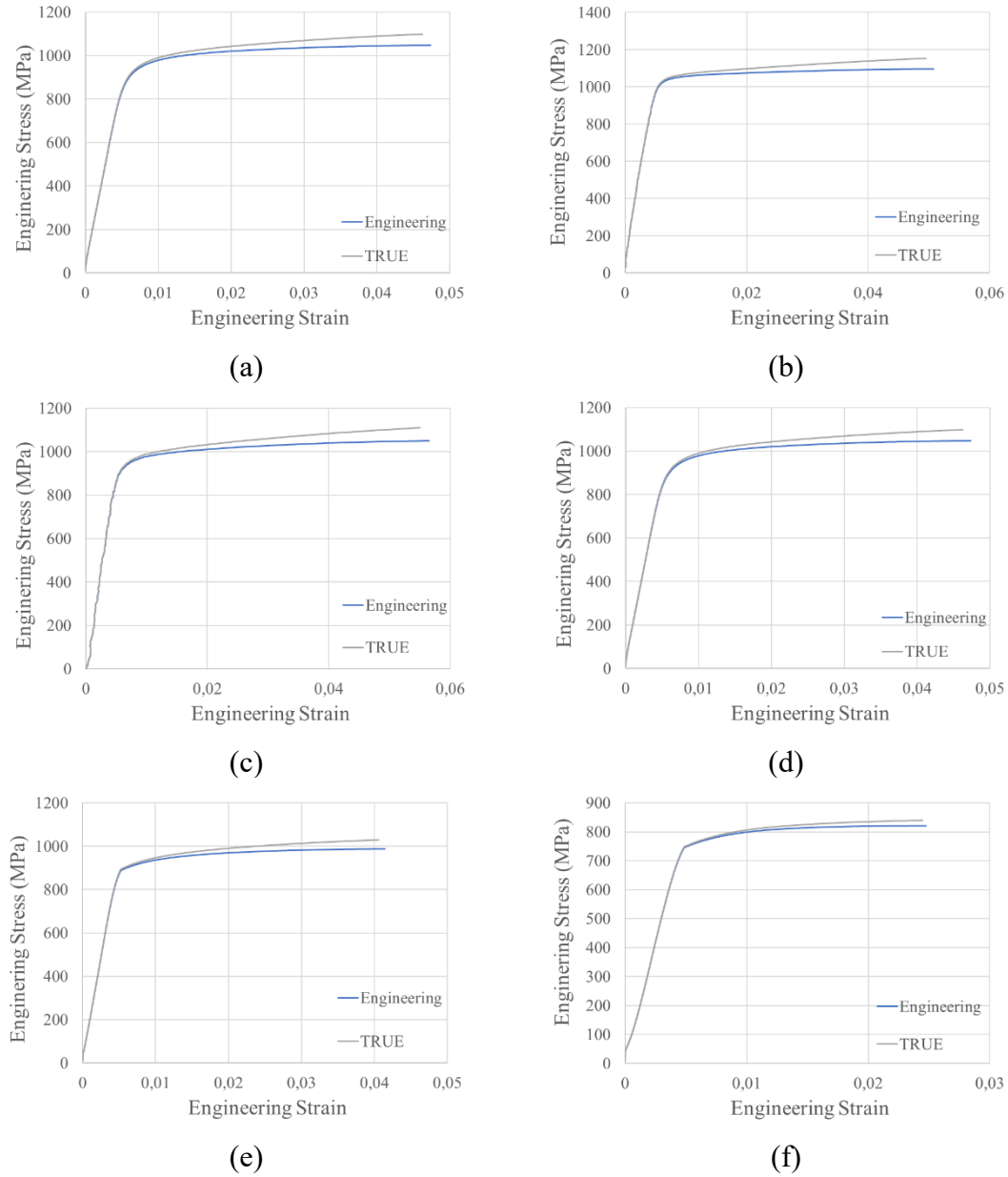

Figure 13. Stress-Strain graphs for S1100 in elevated temperature tensile test result , true data and engineering data from the test. [Graphs from (a to f) are shown temperatures (RT (25 ℃) , 100c, 200℃, 300℃, 400℃, 500℃)]

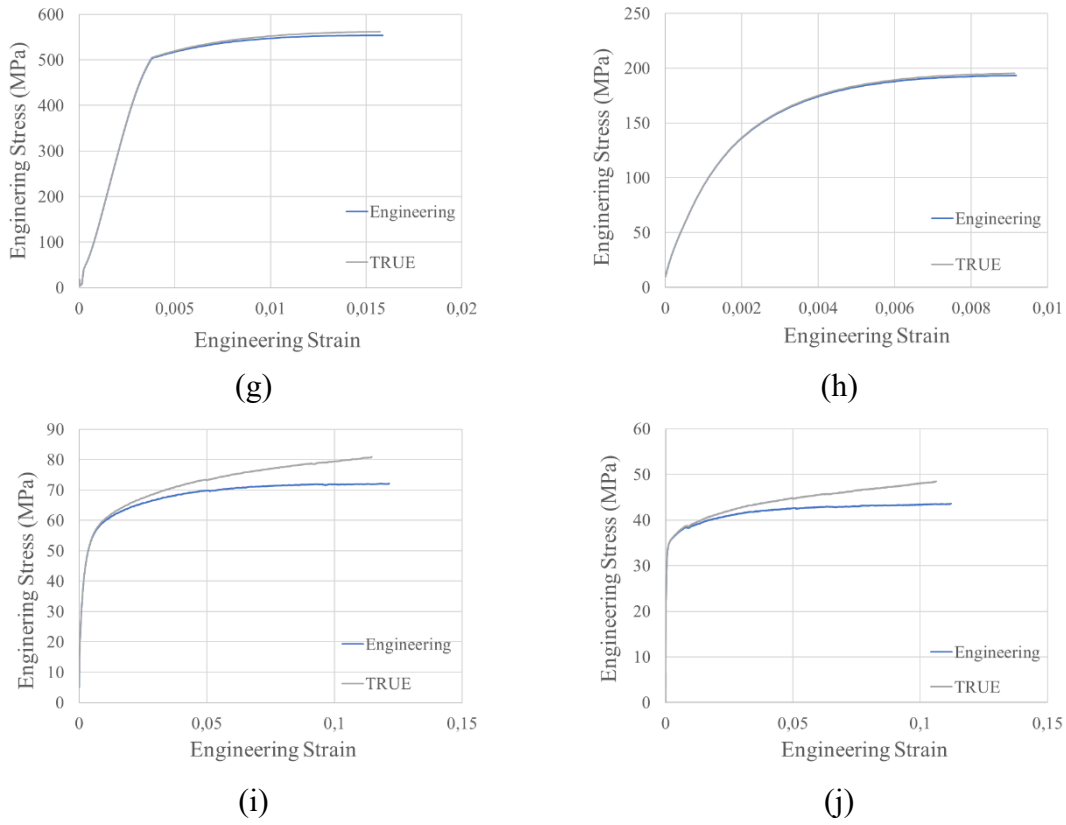

Figure 14. Stress-Strain graphs for S1100 in elevated temperature tensile test results. comparision true data and engineering data from the test. [Graphs from (g to j) are shown temperatures (600℃, 700℃, 800℃, 900 ℃)]

5.2.2 Extrapolations and equations fittings of S1100

The Hollomon model is widely used to evaluate the mechanical behavior of materials, including metals, under different loading conditions, including elevated temperatures. One of the key advantages of the Hollomon model is its simplicity, as it only requires two parameters (*n* and *k)* to describe the relationship between the stress and strain of a material. The Hollomon model assumes that the stress-strain behavior of a material is characterized by a power law relationship, where the stress is proportional to the strain raised to a power (*n*), multiplied by a constant (*k*). This model has been shown to provide a good approximation of the mechanical behavior of many metals, including high-strength steels, over a wide range of temperatures and strain rates. In the case of S1100 steel, the Hollomon model may be particularly appropriate for evaluating its mechanical behavior at elevated temperatures. At high temperatures, the materials microstructure and mechanical properties

can change significantly, and it can be challenging to accurately predict the material behavior using more complex models. The Hollomon mo'el's simplicity and empirical nature make it well-suited to capturing the key aspects of the mater'al's behavior, and it has been shown to provide accurate predictions for high-strength steels under a range of loading conditions. The Hollomon model is a well-established and widely used approach for characterizing the mechanical behavior of metals, including S1100 steel, at elevated temperatures. Its simplicity and empirical nature make it a valuable tool for evaluating the mater'al's behavior in a range of practical applications. In the table below, the results of the tensile test conducted on S1100 UHSS specimens are presented. The stress-strain curve for S1100 UHSS was constructed using the same method as that employed for S960MC, and the resulting data were collected and compiled in the table. These properties represent critical and essential characteristics that enable a scientific evaluation of the speci'en's behavior during the test. By comparing and analyzing these properties, researchers can gain valuable insights into the mechanical behavior of S1100 UHSS and evaluate its suitability for use in elevated temperature applications.

In tabale 7, results are collected and after the evaluation it can be seem the tangent modulus at first has a short decrease in 100℃ then it increases lightly in 200℃, and after that it has other reduction which is more significant in 300 ℃. So overally, the rate of the changes in the tangent modulus in this test is frequently up to 400℃ then after this temperature it is start to decrease fluently from 184870 MPa in 400℃ down to 42691 in 900 ℃ instead of 700 ℃ to 800℃ where this had a other increase this up and down outputs are caused by temperature in this test. but to introduce the yield strength as an important parameter in this study, results in RT started from 1088,4652 MPa and it has a significant changes and decrease to 36,0955 MPa in the 900℃ in the end.this significant changes are same in the Ultimate strength in same temperatures it has a significant decrease from 1135,4675 MPa in RT down to 43,6326 MPa in 900℃.

The mechanical characteristics and strain hardening behavior of S1100 and S960 steels differ significantly from one another. Due to its microstructural features, S1100 steel displays a higher level of strain hardening, leading to an improvement in strength and toughness. As opposed to S1100 steel, S960 steel has a lesser ability for strain hardening, which results in comparatively lower strength and toughness. Additionally, S1100 steel outperforms S960 steel in terms of yield strength and ultimate tensile strength, demonstrating improved load-

bearing capabilities. S1100 steel also has a higher elongation-to-failure, a ductility indicator that shows how easily it can flex plastically before breaking. S960 steel is suited for some applications where these characteristics are essential due to its increased weldability and reduced sensitivity to brittle fracture, it should be highlighted. Considering the trade-off between strength, toughness, ductility, and weldability, the decision between S1100 and S960 steel would rely on the specific needs of the intended application.

Table 7. Mechanical properties for s1100 in elevated temperatures

S1100	Tengent modulus (MPa)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform elongation
RT	194003	1088	1135	0,0609
100 C	192885	1043	1098	0,0495
200 C	195780	940	1050	0,0549
300 C	171133	946	1048	0,0462
400 C	184870	910	987	0,0406
500 C	154939	775	820	0,0244
600 C	143818	522	553	0,0157
700 C	67642	180	193	0,0091
800 C	18579	53	72	0,1146
900 C	42691	36	43	0,1062

A typical mathematical technique for analyzing stress-strain data from tensile testing is the natural logarithm curve. (Figures 16) They are created by comparing the natural logarithms of the genuine stress and strain and visualizing the results. This strategy provides a number of benefits over other approaches to studying stress-strain data, including the ability to take strain rate sensitivity and strain hardening into consideration. Researchers may learn more about the behavior of the material during deformation as well as its resistance to deformation and failure at high temperatures by examining the trends and patterns shown in the natural logarithm curves. To learn more about the mechanical characteristics of the material at high temperatures, the tensile test results for S1100 steel were gathered and examined. In order to get the values for the strain hardening exponent (*n)* and the strength coefficient (*k),* natural logarithm curves were constructed using the data and then fitted to the Hollomon model. for

the S1100, In figure15 and figure 16 natural logarithm curves for the true sigma and true epsilon in the plastic area are shown in the following figures.

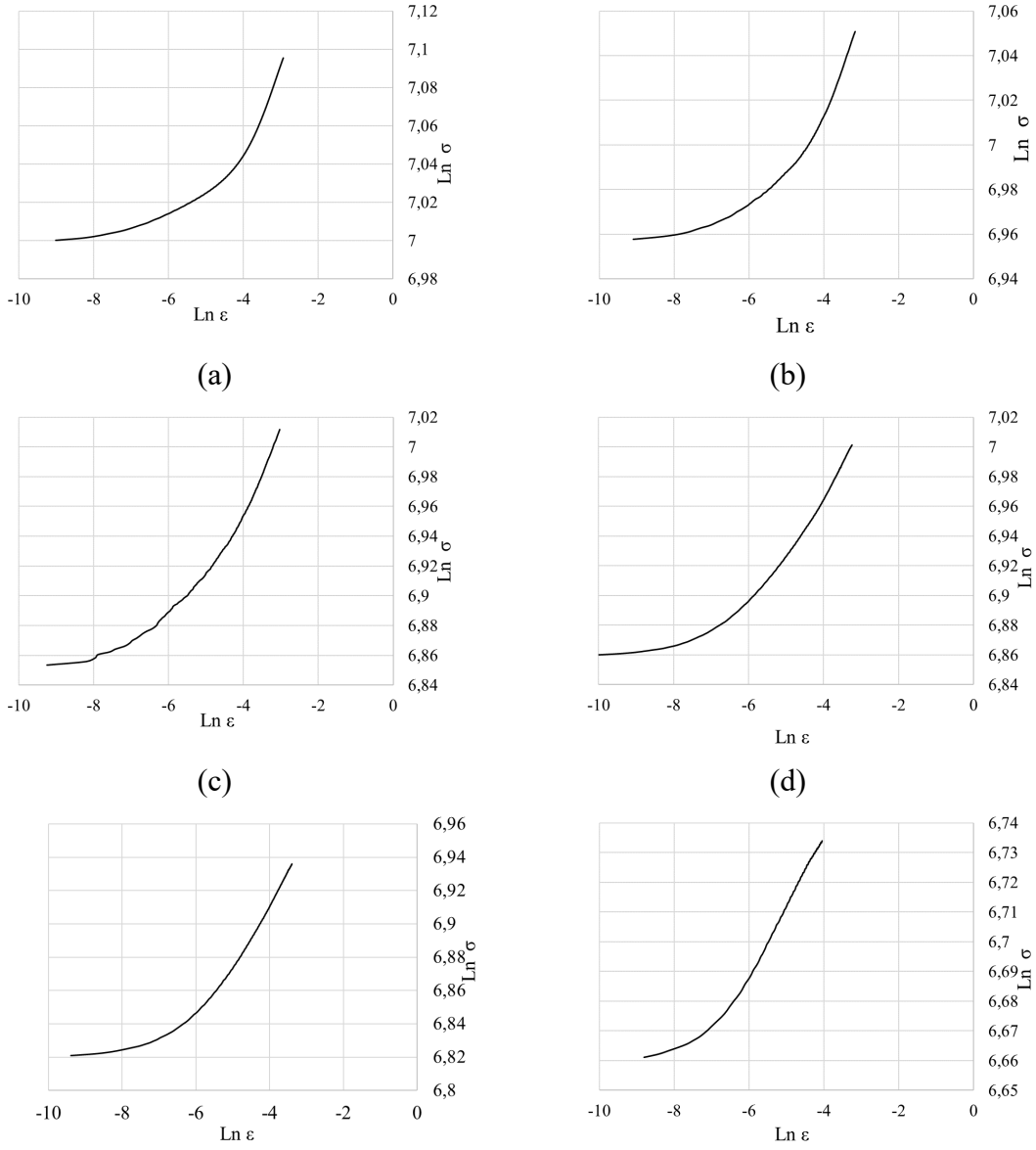

Figure 15. Ln curves of epsilon (ε) and sigma (σ) for S1100 Specimens in tensile test to calculate the n and k from the line equation and put in the Hollomon model. [Graphs from (a to f) are shown temperatures (RT (25 ℃) , 100c, 200℃, 300℃, 400℃, 500℃]

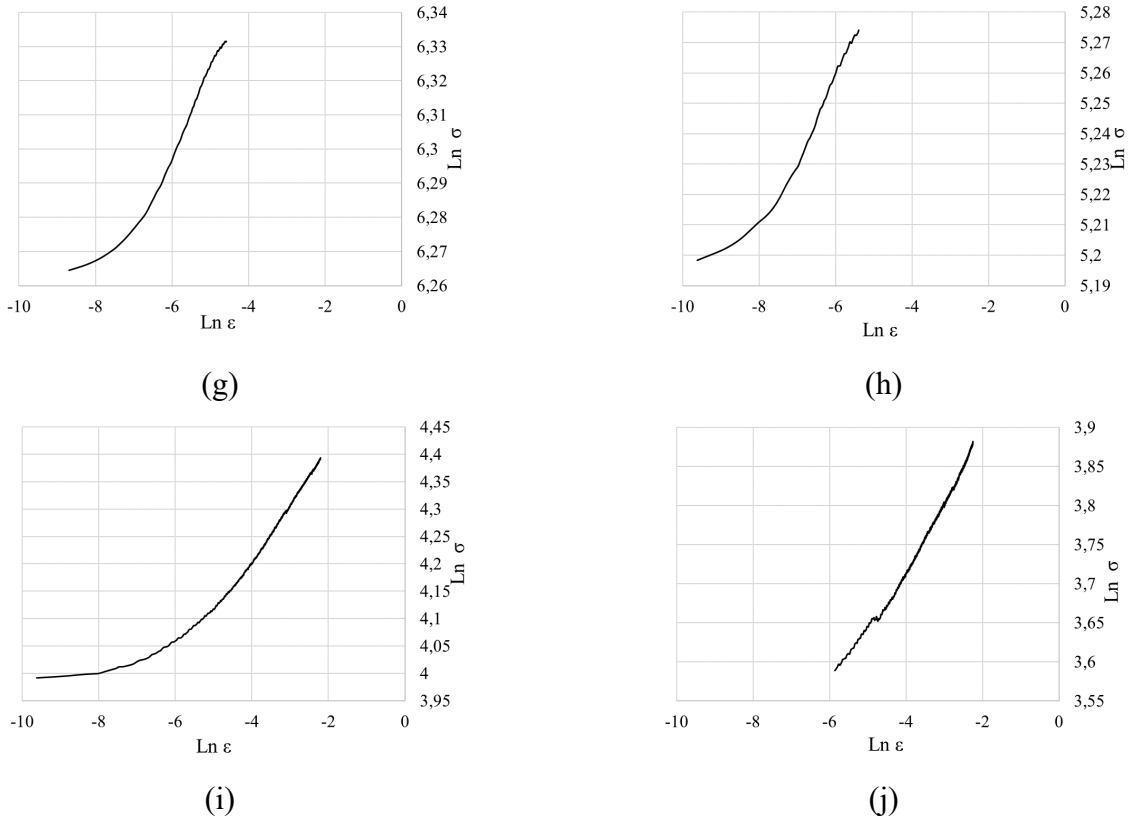

Figure 16. ln curves of epsilon (ε) and sigma (σ) for S1100 Specimens in tensile test to calculate the n and k from the line equation and put in the Hollomon model. [Graphs from (g to j) are shown temperatures (600℃, 700℃, 800℃ , and 900 ℃)]

Upon careful analysis of Figure 16, the data relevant to our Hollomon equation (2) has been extracted and compiled in Table 8. By extracting the relevant data from natural logarithem figures, we have constructed Table 8, which provides a consolidated overview of the key parameters for the Hollomon equation. The parameters, namely the strain hardening exponent (*n*), the strength coefficient (*k*), and the coefficient of determination (*R^2*), are included in table 8. The strain hardening exponent *(n)* characterizes the material's ability to resist further deformation as plastic strain increases, while the strength coefficient (*K*) represents the initial strength or yield stress. Additionally, the coefficient of determination (*R^2*) indicates the goodness-of-fit between the experimental data and the Hollomon equation model, offering insights into the accuracy and reliability of the equat'on's predictions. The inclusion of Table 9, with its concise presentation of the relevant Hollomon equation parameters, contributes to a more precise understanding of the mater'al's mechanical behavior and its response to applied loads. The availability of this data enhances

our ability to make informed decisions in engineering design, material selection, and performance prediction for various applications. This data has been thoughtfully compiled and presented in Table 9, offering a comprehensive overview of the key parameters (*n, k, R^2*) crucial to the Hollomon equation (2).

Table 8. [n, k, R^2] related to the Ln curve for the S960 tensile test

S1100	RT°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	800°C	900°C
n	0,0234	0,0233	0,0367	0,032	0,0285	0,0192	0,0214	0,0227	0,0865	0,0848
k	1272	1226	1222	1207	1123	901	619	220	96	57
R^2	0,837	0,8756	0,927	0,938	0,9316	0,9645	0,9645	0,9554	0,9604	0,9595

Following the data collection process, the collected data points were employed to construct the Hollomon curves. These curves serve as visual representations of the material's response to applied loads and provide valuable insights into its deformation characteristics. Drawing the Hollomon curves using the collected data enables a comprehensive understanding of the material's mechanical behavior under specific conditions.

By employing the Hollomon equation, which incorporates the determined *n* and *k* parameters, we can accurately predict the material's mechanical response, including its ability to resist deformation and withstand applied stresses. The Hollomon curves, derived from the collected data, provide a graphical representation of the material's stress-strain relationship and allow for the estimation of its mechanical properties at various levels of plastic strain. The outcomes derived from the analysis of the natural logarithm curves have facilitated the collection of pertinent data required to determine the n and k parameters for the application of the Hollomon equation to S1100 steel. The subsequent construction of the Hollomon curves utilizing the collected data provides a visual representation of the material's mechanical behavior, enabling a comprehensive understanding of its deformation

characteristics. These findings have practical implications for engineering design and analysis, as they enhance the predictive capabilities of the Hollomon equation and contribute to the broader knowledge base in the field of materials science and engineering.

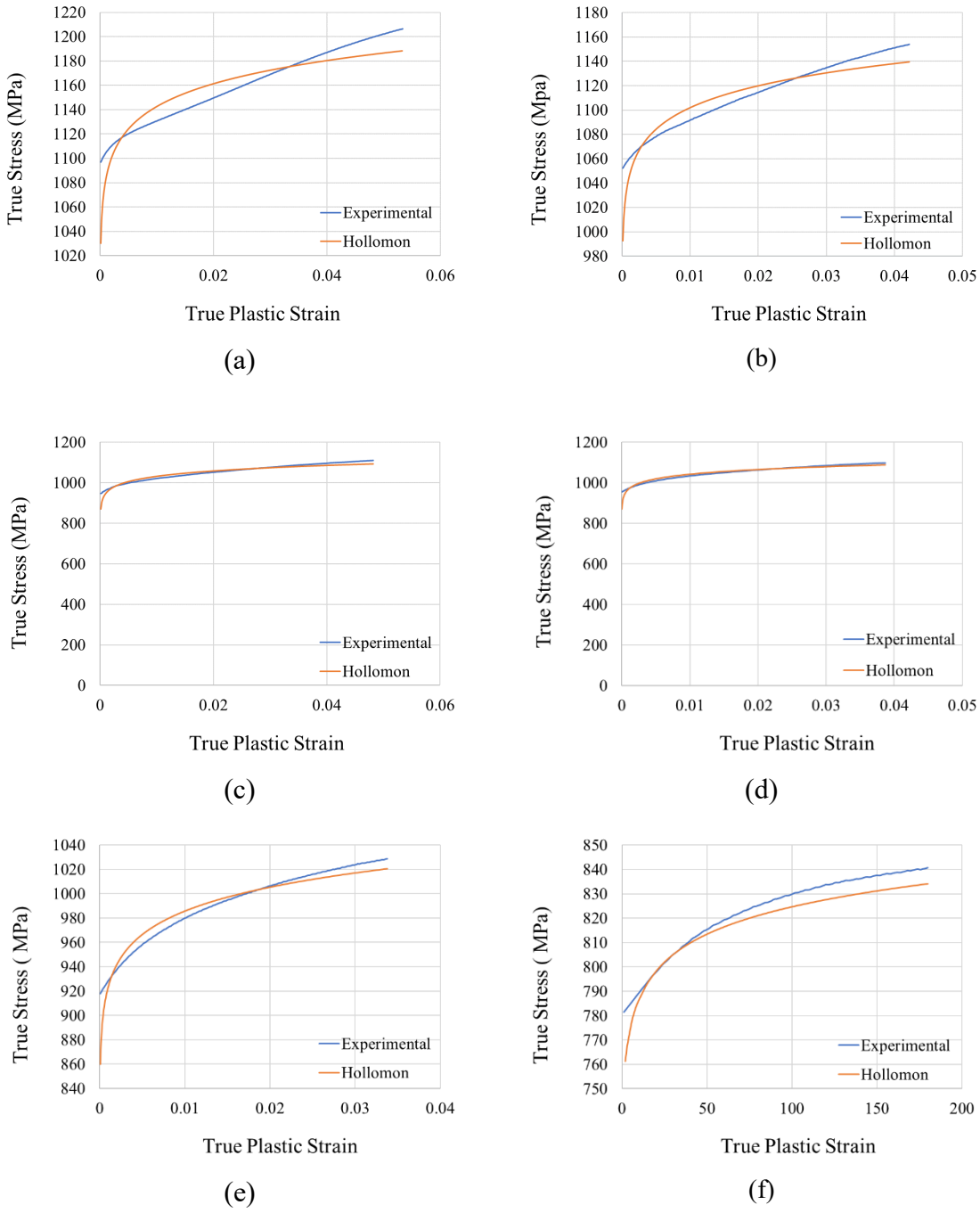

Figure 17. fitting hollomon model and true plastic stress-strain curve for S1100 UHSS specimens in the tensile test in elevated tempuratures [(a)to (f)are remain the temperatures, RT(25 °C), 100°C, 200°C, 300°C, 400°C, 500°C]

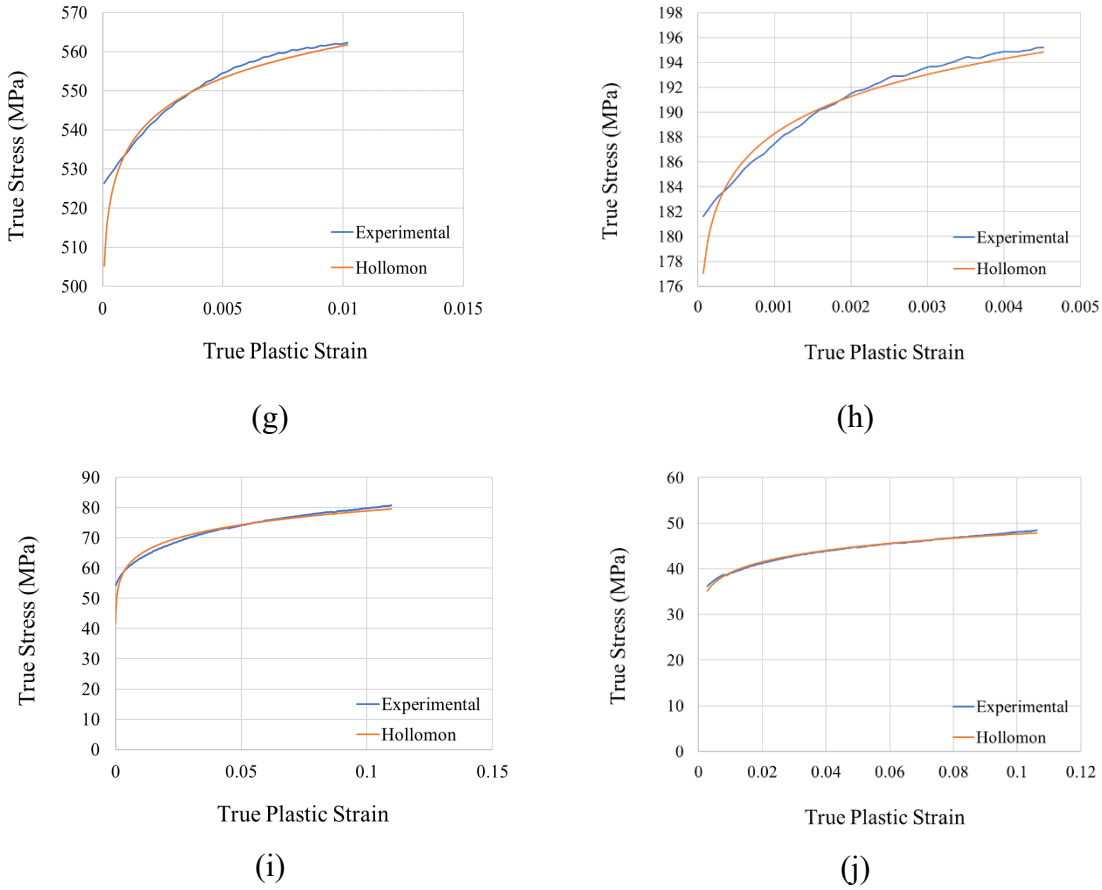

Figure 18. fitting hollomon model and true plastic stress-strain curve for S1100 UHSS specimens in the tensile test in elevated tempuratures [(g) to (j)are remain the temperatures, 600 °C, 700°C, 800°C, 900°C]

In comparison to S960MC steel, the Hollomon model was found to provide a better fit for modeling the mechanical behavior of S1100 steel across most temperatures. The Hollomon curve for S1100 steel demonstrated a greater degree of linearity, with a higher R-squared value, indicating a stronger correlation between the model and experimental data. Furthermore, the Hollomon model was able to accurately capture the stress-strain relationship of S1100 steel in tension, including the material's flow stress and strain hardening behavior. It should be noted that while the Hollomon model provided a good fit for S1100 steel across all temperatures, there were some deviations from the model predictions at higher temperatures. These deviations could be attributed to the influence of other factors, such as thermal softening and microstructural changes, that were not explicitly accounted for in the model.

6 Conclusion

Ultra-high-strength steel (UHSS), renowned for its unique microstructure and exceptional mechanical properties, plays a vital role in automotive, aerospace, and military industries. To shape UHSS components and enhance their performance, processing methods like roll forming and thermomechanical treatments have been employed. However, challenges persist in overcoming toughening and achieving defined mechanical characteristics in ultra-high-strength low-alloy steels. In the context of engine downsizing, high-strength engine fasteners are crucial for withstanding increased mechanical and thermal demands.

A straightforward yet efficient method for simulating the mechanical behavior of high-strength steels at high temperatures is the Hollomon model. This empirical model accurately captures the key elements of material behavior under different loading conditions, such as for S960 and S1100 steels. Tensile testing revealed that the mechanical properties of S960 and S1100 steel undergo significant changes as the temperature increases. Specifically, strength and ductility decline at higher temperatures, consistent with previous research on high-strength steels. The Hollomon curve, generated using the n and k parameters obtained from tensile test results for S1100 steel, closely approximated the material's behavior under various loading situations. The Hollomon model accurately predicted the mechanical behavior of S1100 steel at high temperatures when compared with actual and computer-simulated findings. Consequently, the Hollomon model can be a useful tool for forecasting the mechanical behavior of S1100 steel in real-world scenarios, providing design recommendations and enhancing the performance of high-strength steel structures in high-temperature environments.

Based on this study, the Hollomon model can effectively describe the mechanical behavior of ultra-high-strength steels, including S960 and S1100, at high temperatures. Furthermore, this research offers valuable insights into the material characteristics of S960 and S1100 steel under different loading scenarios, aiding in the design of high-strength steel structures that perform well in hot environments.

6.1 Proposal for future studies

Examination of S1100 UHSS microstructure progression at high temperatures: Future research might concentrate on examining how the microstructure of S1100 UHSS evolves under various increased temperatures utilizing methods including optical microscopy, scanning electron microscop (SEM), and transmission electron microscopy (TEM). It is possible to create a link between microstructure and mechanical characteristics, which will be helpful for creating high-temperature-resistant steels. Comparison of several models for forecasting UHSS's mechanical performance at extreme heat Future research might compare the Hollomon model to other models for forecasting the mechanical behavior of UHSS at high temperatures, such as the Ludwik model, Swift model, and Johnson-Cook model. These models' applicability and accuracy may be compared, allowing for the best model to be chosen for forecasting the mechanical behavior of UHSS in various applications.

Analyses of the mechanical characteristics of UHSS at high temperatures and the effects of alloying components Future research can concentrate on examining the impact of various alloying components, including as Ni, Cr, Mo, and V, on the mechanical characteristics of UHSS at high temperatures. A novel UHSS with superior high-temperature mechanical qualities may be designed by measuring and comparing the mechanical properties of various alloys, such as tensile strength, yield strength, and elongation. Future research can model the mechanical behavior of UHSS at increased temperatures using numerical simulation techniques like finite element analysis. To verify the correctness of the simulation model and aid in the design of UHSS components for high-temperature applications, the simulation results may be compared with the experimental findings.

Examining how heat treatment affects the mechanical properties of UHSS at high temperatures: Future research can concentrate on examining how heat treatment affects the mechanical behavior of UHSS at high temperatures. Applying various heat treatment techniques to UHSS specimens, such as quenching and tempering, annealing, and normalizing, and comparing the mechanical properties before and after the heat treatment will help to improve the UHSS heat treatment process. In conclusion, there are significant differences in the mechanical characteristics and strain hardening behavior of S1100 and S960 steels. Compared to S960 steel, S1100 steel displays a higher level of strain hardening, increasing its strength and toughness. Additionally, S1100 steel has improved yield strength

and ultimate tensile strength, suggesting that it can support heavier loads. The increased elongation-to-failure of S1100 steel also suggests better ductility and deformability prior to fracture. Contrarily, S960 steel has a lower strain hardening capability than S1100 steel, which leads to comparatively lower strength and toughness. Considering the trade-off between strength, toughness, and ductility, the decision between S1100 and S960 steel relies on the particular needs of the application.

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