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MAJOR PROJECT:

INVESTIGATING THE INFLUENCE OF MACHINING VARIABLES AND DEFECTS ON MACHINED COMPONENTS TENSILE PROPERTIES

———— MAY 19TH 2025 ————

MODULE: MAJOR PROJECT

MODULE CODE: ACMA6013

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WORD COUNT:

10608

Abstract

The mechanical reliability of medium-carbon EN8 steel in service is governed by its bulk composition and the surface condition imparted during machining. This dissertation quantifies how three practical manufacturing variables—surface roughness, coolant usage during turning, and a deliberately machined surface defect—affect the uniaxial tensile response of cold-drawn EN8. Fifteen cylindrical specimens (25 mm gauge length, ≈ 5 mm diameter) were produced on a CNC lathe and grouped as follows: 6.4 $\mu\text{m Ra}$ (flood-cooled), 3.2 $\mu\text{m Ra}$ (flood-cooled), 1.6 $\mu\text{m Ra}$ (flood-cooled), 1.6 $\mu\text{m Ra}$ (dry-cut), and 3.2 $\mu\text{m Ra}$ with a circumferential notch. Tensile tests were executed to ISO 6892-1 on a 100 kN universal tester, while optical microscopy (60 $\times$) verified the microstructure. Statistical repeatability was ensured by testing three specimens per condition and reporting the mean, standard deviation, and coefficient of variation. Results show that surface finish exerts the most decisive influence: refining roughness from 6.4 $\mu\text{m Ra}$ to 3.2 $\mu\text{m Ra}$ elevated ultimate tensile strength (UTS) from 799 MPa to 833 MPa (+ $\approx 4\%$) and yield strength by up to 15 %, with no further UTS gain at 1.6 $\mu\text{m Ra}$. Eliminating coolant had no statistically meaningful effect; dry-cut 1.6 $\mu\text{m Ra}$ specimens mirrored the flood-cooled counterparts (UTS ≈ 822 MPa versus 809 MPa). In stark contrast, a single circumferential notch cut UTS to 737 MPa (- 10–15 %) and curtailed post-yield ductility, precipitating quasi-brittle failure. Microscopic examination confirmed a standard ferrite–pearlite lamellar matrix across all batches, indicating that the observed mechanical differences stem from surface-integrity effects rather than metallurgical changes. Collectively, the study identifies finish turning to $\sim 3.2\ \mu\text{m Ra}$ as the most cost-effective route to enhance strength, demonstrates that coolant choice may be dictated by tool life rather than material performance, and underscores the critical need to avoid surface defects in safety-critical EN8 components.

Acknowledgements

My deepest gratitude goes first to my partner, Grisial Annest, whose unwavering support, patience, and encouragement sustained me throughout this journey.

I am profoundly thankful to Dr. Kelvin Lake for his exceptional supervision and steadfast guidance at every stage of this project. His expertise and constructive insight were pivotal to the success of the research.

I also sincerely thank Rhys Brannan of Swansea University for the precise machining of the test specimens, which provided a solid foundation for the experimental work.

Further appreciation is due to Mark Fall of the University of Wales Trinity Saint David for his invaluable assistance and technical insight during the tensile testing experiment.

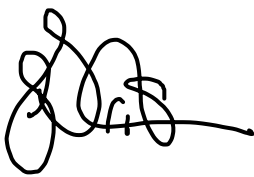
Finally, I sincerely thank Mark Broadhead for his support with microscopy analysis.

To all of you, your expertise, time, and commitment have been essential in completing this dissertation.

Declaration of Authenticity.

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination, which has led to the award of a degree.

Signed:



Date:18/05/2025

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1.Introduction

The mechanical performance of engineering materials is paramount in ensuring the reliability and safety of structural and mechanical components across various industries (Mouritz, 2012). Among these materials, medium carbon steels, such as EN8, are extensively utilised due to their balanced combination of strength, ductility, and wear resistance (Singh, 2012). EN8 steel, characterised by its carbon content ranging between 0.37% and 0.44% (McCauley, 2000) is widely employed in applications requiring moderate strength and toughness, including shafts, bolts, and gears (Islam and Rashed, 2019). Understanding the tensile properties of EN8 steel under different variables is essential for optimising its performance and extending its service life.

Tensile Testing serves as a fundamental method for evaluating the mechanical properties of materials, providing critical insights into their behaviour under uniaxial stress (Hearn, 1997). This test measures key parameters such as ultimate tensile strength (UTS), Yield Strength and Young's Modulus (ISO, 2019), which are indispensable for material selection and engineering design. However, the tensile properties of EN8 steel can be significantly influenced by various factors, including thermal treatments (Chandran et al., 2022), surface conditions (Chen et al., 2023) and the presence of defects. Investigating these variables is crucial for tailoring the material properties to specific applications and enhancing their overall performance.

This dissertation examines the tensile properties of EN8 medium carbon steel influenced by three distinct variables: the use of coolant during processing, surface finish quality, and the introduction of intentional defects. The justification for selecting these variables addresses critical real-world applications that affect the reliability, safety, and performance of EN8 in engineering applications; yet their combined effects on EN8 steel's tensile properties remain underexplored.

1.1 Research Aim and Objective

The primary objective of this research is to evaluate the tensile properties of EN8 medium carbon steel when varying machining variables are applied to test specimens. Specific objectives include:

1.1.1 Application of coolant during machining operations

The application of coolant during metal processing, such as machining or heat treatment, is a common practice aimed at controlling the temperature, reducing thermal stresses, and improving surface integrity (Zheng Yang et al., 2023). Coolants can influence the microstructure of EN8 steel by affecting grain size, phase transformations, and residual stress distribution, which in turn impact tensile properties (Chandran et al., 2022).

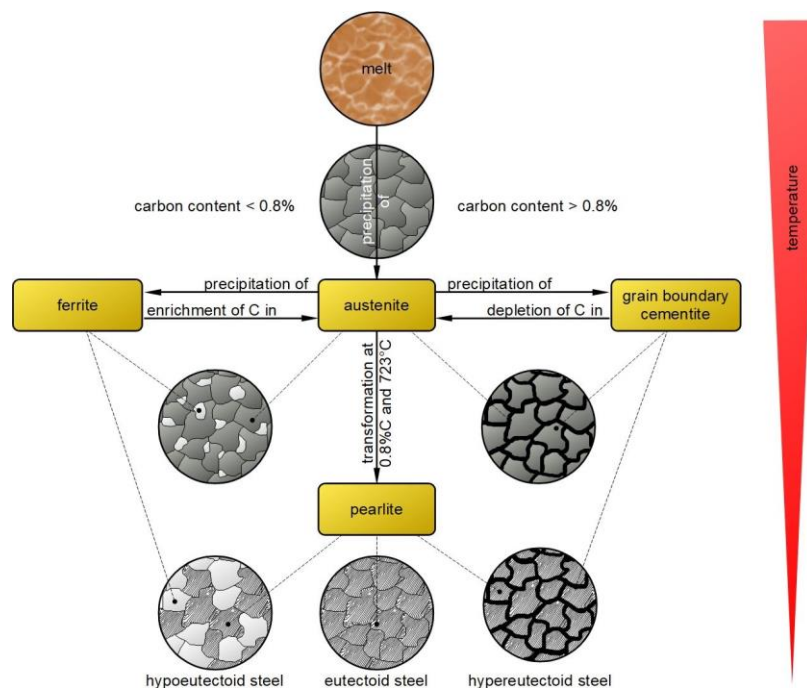


Figure 1-Overview of the microstructure formation of steel. Source:('Summary of the phase transformations of steel | tec-science', 2018)

The grain size of ferrite–pearlite plays a crucial role in modifying its properties, as the boundaries between grains serve as obstacles to dislocation movement and crack propagation (Wang et al., 2018). The material adheres to the Hall–Petch relationship, which posits that grain size and strength have an inversely proportional relationship; as grain size decreases in iron and steel, material strength increases (Li et al., 2016). The final grain size is governed almost entirely by the cooling rate from the austenitising temperature (Callister and Rethwisch, 2020). Increasing the cooling rate of steel limits the grains' opportunity to grow, resulting in a progressively finer structure. Annealing, which involves slow cooling in a furnace, leaves the coarsest grains, giving the lowest strength but the greatest ductility and ease of cold-forming (Rathinasuriyan et al., 2023). Normalising in still air refines the structure, offering a balanced mix of strength, toughness and machinability (Liu et al., 2016). The fastest route to cooling-water or oil quenching (Srivastava et al., 2021)- maximises strength and fatigue resistance at the expense of higher residual stress and a greater risk of quench cracking or distortion (Šolić et al., 2018). In summary, understanding how different cooling regimes alter the tensile characteristics of EN8 steel can inform optimal processing techniques to achieve the desired mechanical performance.

1.1.2 Surface Finish

Surface finish refers to the texture and smoothness of the material's surface after processing (McCauley, 2000). A finer surface finish typically indicates fewer surface imperfections and lower stress concentrations, which can enhance tensile strength and fatigue resistance (Persson, 2023). Conversely, a rougher surface finish may introduce stress risers that act as initiation points for cracks, thereby reducing the material's tensile capacity (Budynas et al., 2011). Surface finish is commonly measured in micrometres (μm) and can be quantified using several methods. International standards, such as ISO 4287 (profile parameters)(ISO, 1997) and the newer ISO 21920-2 (profile method)(NSAI, 2022), outline a set of roughness descriptors, with arithmetic-average roughness (R_a), root mean squared roughness(R_q), and average maximum height roughness (R_z) being the most frequently used(Ruzova and Haddadi, 2025),(Hamzah et al., 2022). While R_a and R_q offer a single-value measure of overall roughness amplitude, R_z is more attuned to distinct deep valleys or high peaks of the surface of the material (Ruzova and Haddadi, 2025). Additional parameters, such as R_{Sm} for mean spacing and R_{sk} for skewness, are utilised when the lay, lubrication,

or contact behaviour is critical (Zhu and Huang, 2017). Ra is most commonly used within industry applications (Hamzah et al., 2022), and it is formally defined as the mean of the absolute profile height deviations taken over a specified sampling length (ISO, 1997). The quantity is therefore an amplitude-only statistic, insensitive to whether the profile contains a few tall peaks or many shallow ones. Due to its simplicity, it has secured its place being used widely in numerous manufacturing drawings and quality manuals (McCauley, 2000). Investigating the relationship between surface finish and tensile properties of EN8 steel provides valuable information for manufacturing processes where surface quality is critical to component performance (Persson, 2023).

1.1.3 Surface defects

Introducing controlled defects into a material allows the study of their effects on mechanical properties under tensile loading (Wang et al., 2022). Defects such as notches, voids, or inclusions can serve as stress concentrators (Callister and Rethwisch, 2020), influencing the initiation and propagation of fractures (Hearn, 1997). By intentionally incorporating specific defects into EN8 steel specimens, this study aims to quantify their impact on tensile behaviour and identify the threshold levels at which defects significantly degrade material performance. This knowledge is essential for quality control and predicting components' lifespan subjected to service-induced defects.

1.2 Methodological Approach

This study adopts a systematic experimental method, involving the preparation of EN8 steel specimens exposed to different cooling processes, surface finishes, and defect introductions. To ensure the reliability and consistency of the results, tensile tests were carried out in accordance with ISO 6892-1 standards. An optical microscope was used for microstructural analysis, which complements the mechanical testing by offering insights into the material changes caused by the examined variables. Statistical analysis was conducted to interpret the data and identify significant correlations between the tested variables and tensile properties.

1.3 Research Significance

The relationship between cooling methods, surface finish, and material defects presents a comprehensive approach to understanding the tensile properties of EN8 medium carbon steel. This dissertation investigates how these factors influence the tensile behaviour of EN8 steel. While individual studies have examined the effects of each variable separately, there is a lack of research exploring their impact in a unified study. As a secondary research objective, this project's experimental and theoretical findings were utilised to enhance the understanding and application of tensile testing procedures at the Author's place of work- the Engineering Department at NPTC Group of Colleges. NPTC Group is a major further education and skills provider in Wales, formed on 1 August 2013 through the merger of Neath Port Talbot College (initially founded in 1931) and Coleg Powys (NPTC, 2025). It teaches approximately 20,000 learners annually and serves a catchment area covering about 30 % of Wales's land mass, stretching from coastal Neath Port Talbot into rural Powys.

1.4 Dissertation Structure

Chapter 2 outlines a clear timing plan that logically maps out each project phase. Chapter 3 presents a thorough literature review, summarising current research on the tensile properties of medium carbon steels and the effects of cooling, surface finish, and defects. Chapter 4 details the experimental methodology, including specimen preparation, testing processes, and analytical techniques. Chapter 5 displays the results of the tensile tests in both tabular and graphical forms. Chapter 6 examines the findings, discusses microstructural analyses within the context of the research goals and existing literature, and emphasises significant insights and implications. Lastly, Chapters 7 and 8 conclude the dissertation, providing recommendations for future research and practical applications based on the study's results.

2.Timing plan

This chapter depicts two Gantt charts created using Microsoft Project: a formative sample produced at the start of the project and a summative Gantt chart reflecting a revised plan upon completion.

2.1 Original Timing Plan

The Gantt chart in Fig.2 shows the original timing plan proposed for this project. As illustrated, the project was organised into four phases: Initiation, Creation and Experimentation, Analysis of Findings, and finally, Submission and Presentation.

The plan for the initiation phase consisted of creating my project proposal and conducting early research, culminating in an interim Viva. This phase was proposed to last 70 days, from 06/09/24 to 13/12/24. The creation and experimentation phase was scheduled to last 56 days, from 13/12/24 to 28/02/25. During this phase, the experimental methodology was written and executed to capture the quantitative and qualitative data necessary for analysis. The third phase- Analysis of Findings- was projected to span 57 days, from 28/02/25 to 19/05/25. This phase focused on processing the data captured in the previous phase and producing a report detailing my analysis and findings. The final phase- Submission and Presentation- was forecasted to last 30 days, from 19/05/25 to 27/06/25. This phase concludes the project and is marked by the submission of this dissertation and the final Viva presentation.

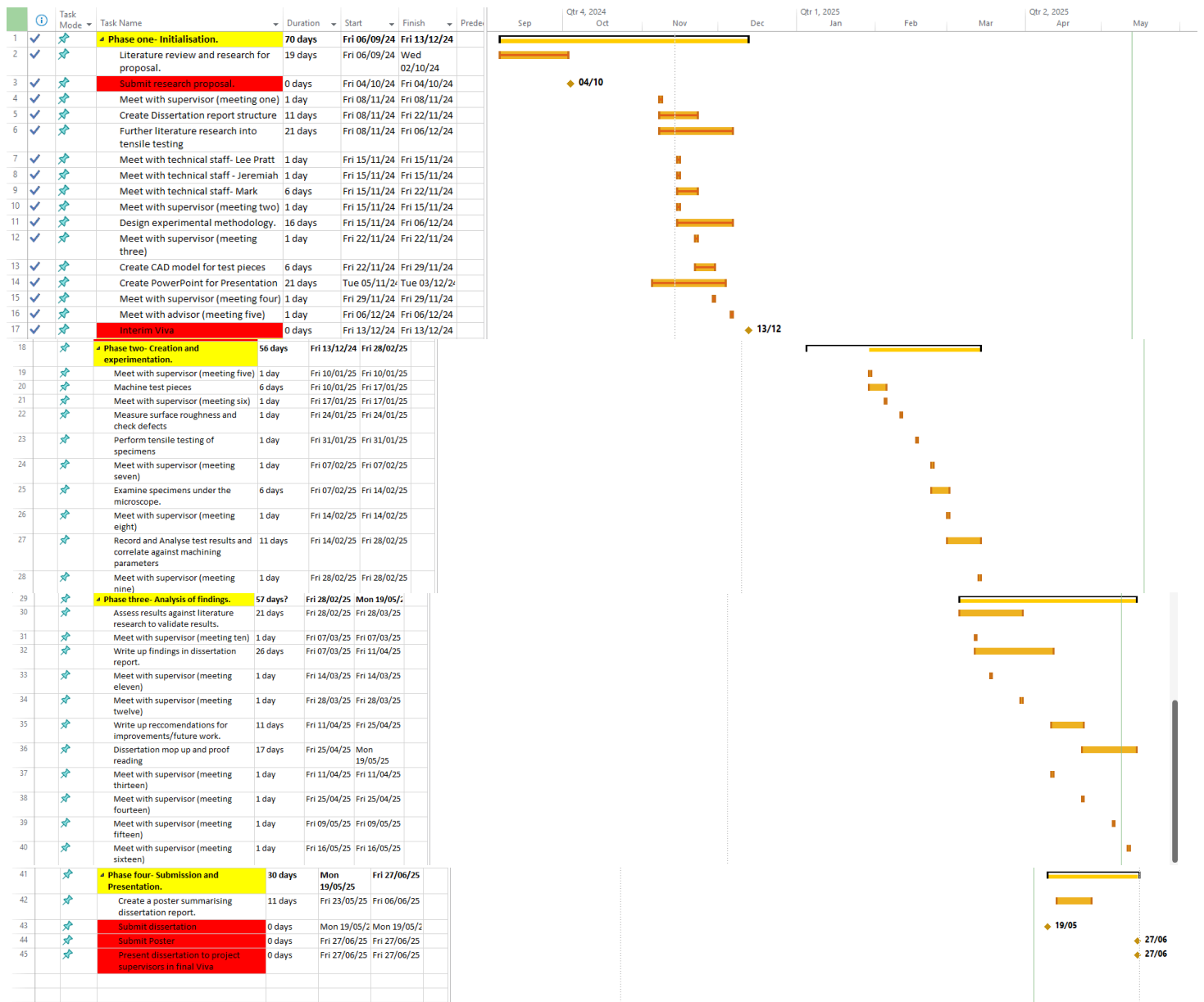


Figure 2-Original Gantt chart of the timing plan

2.2 Revised Timing Plan

Upon completion of this dissertation, a revised Gantt chart is presented in Fig.3 to reflect changes made to the original plan. The first phase was completed as planned within the initially proposed timeframe and did not experience any setbacks; however, this was not the case for the following two phases. Delays in manufacturing the test samples pushed the closing date of phase two to 09/04/24 (as indicated by the red bar next to phase two). This delay had a downstream effect on phase three, extending the completion of the dissertation to 11/05/25. The final phase returned to plan and was completed as expected by 19/05/25.

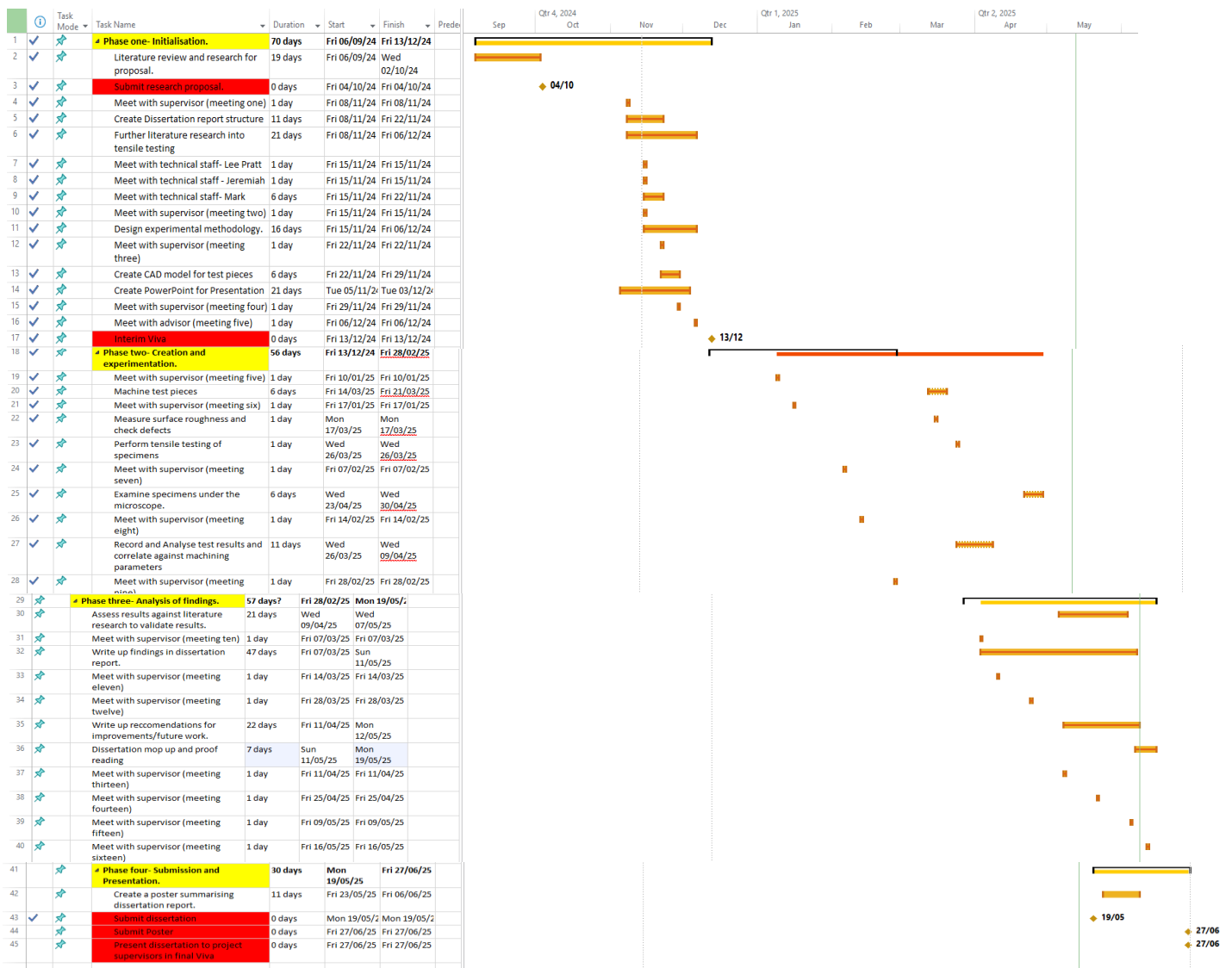


Figure 3-Revised Gantt chart of the timing plan

3.Literature Review

3.1 Tensile Testing

Tensile Testing is a widely utilised method in materials science, especially for evaluating the mechanical properties of metals (Harding et al., 1960), (Banerjee et al., 2021). This type of testing provides critical information about the behaviour of metals under tension, including their Tensile Strength, Yield Strength, Elongation, and Elastic Modulus (Callister and Rethwisch, 2020). The process is essential for determining how a metal will respond to mechanical stresses in practical applications (Hearn, 1997)making it key in quality control (Loveday et al., 2004), material selection (Callister and Rethwisch, 2020)and engineering design (McCauley, 2000).

The Tensile Testing process starts with the meticulous preparation of test specimens. These specimens must be shaped and sized according to established standards to ensure consistency and reliability in the test outcomes. Standards such as ASTM E8/E8M and ISO 6892-1 are commonly adhered to for metallic materials. These standards outline precise guidelines regarding the specimens' shape, dimensions, and surface integrity. The most frequently used shapes are dog-bone or cylindrical geometries, designed to ensure failure occurs within the gauge section where stress is most uniform. Various factors can affect the results of a tensile test, making it crucial to control these variables for achieving accurate and reproducible data.

The Tensile Test is conducted using a universal testing machine (UTM) (Fig.4) specifically designed to apply a uniaxial tensile force to the metal specimen (Fábián and Gergely, 2020). The UTM setup includes grips that securely hold the specimen (Fig.15), a load cell that measures the force applied, and an extensometer or strain gauge to measure the elongation of the specimen during testing precisely (Huňady et al., 2024). Accurate data collection requires high-precision equipment to capture both the applied load and the corresponding elongation of the specimen in real-time. Once the specimen is mounted, the tensile force is applied at a controlled rate, typically in accordance with standardised strain rates such as those outlined in ASTM E8 (2021). This controlled loading ensures the material's response is

captured accurately without introducing additional variables from testing equipment or procedures.



Figure 4-Universal Testing Machine (UTM).Source :(labrotovap, 2020)

During the test, the machine continually records the force exerted on the specimen (Fig.16) and its corresponding elongation until it eventually fractures (Fig.17). The gathered data produces a stress-strain curve (Figs. 25, 27, 29 & 31), essential for determining important material properties (Callister and Rethwisch, 2020). This curve reveals various mechanical properties, including yield strength, which signifies the stress level at which the material begins to deform plastically; UTS, representing the maximum stress the metal can bear

before necking happens; and elastic modulus, which quantifies the material's stiffness (John, 2003). Moreover, the elongation at break measures ductility, showing how much the material can stretch before failure (Dowling et al., 2020). The results from several specimens are then statistically analysed to find mean values and standard deviations, ensuring that the reported values are robust and representative of the material's characteristics (ISO 6892, 2019; ASTM 8M, 2021). The principles discussed in this section are applied in practice in Chapter 4.4.



Figure 5-Representation of different types of tensile test specimens. Source:(Mechanical Test Specimens - Tensile Test Specimens - Fracture Mechanics Specimens, 2025)

3.2 Surface finish and its effect on tensile properties

Research suggests that surface finish can be a critical factor in test reliability, as imperfections can act as stress concentrators, potentially skewing results (Persson, 2023). A rough surface finish, often caused by coarse feed rates (Fig.6) (Abellán-Nebot et al., 2024), scratches, or tool marks (Ghazali et al., 2019), may reduce the UTS by creating stress concentrations that act as crack initiation sites (Chen et al., 2023). In contrast, a smooth surface finish enhances strength by distributing the applied load more evenly and minimising these stress risers (Wang et al., 2024).

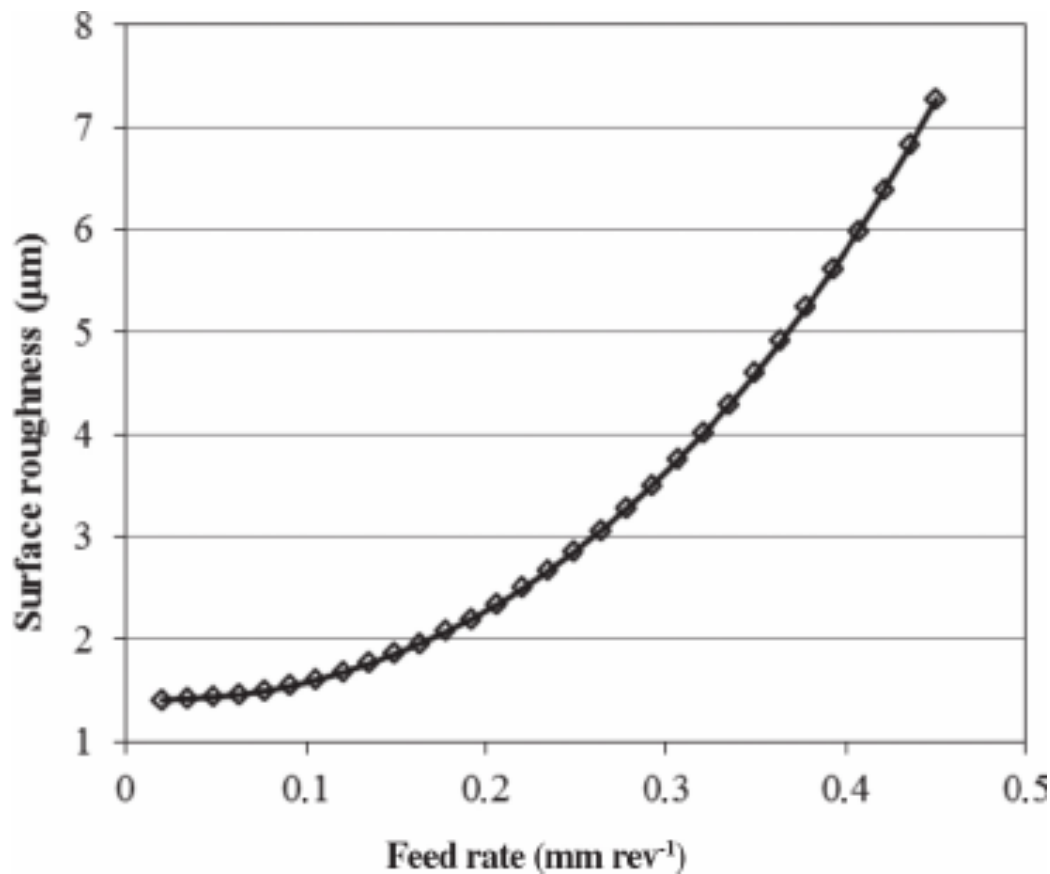


Figure 6-Diagram of a CNC lathes feed rate vs surface finish. Source:(Aldaş et al., 2014)

Yield Strength is generally less affected by surface finish than UTS, though rougher surfaces can lead to slightly lower yield strength due to the premature initiation of plastic deformation (Nafar Dastgerdi et al., 2021). Ductility, on the other hand, is significantly impacted, as rough finishes reduce elongation before failure by promoting early crack initiation (Chen et al., 2023). A smoother finish allows the material to undergo greater deformation before fracture, improving overall ductility (Zhu et al., 2021).

Fatigue strength is one of the most sensitive properties to surface finish. Rough surfaces with machining imperfections create stress concentrations that accelerate crack growth, lowering fatigue resistance (McKelvey and Fatemi, 2012). In contrast, polished or finely machined surfaces improve fatigue life by minimising defects that can lead to premature failure (Ye et al., 2021). Additionally, surface finish influences fracture behaviour, with rough surfaces promoting brittle fracture and smooth surfaces encouraging ductile fracture by allowing more plastic deformation before breaking (Liu and Nambu, 2024).

Another critical factor is the effect of machining on residual stresses. Rough machining methods, such as turning or milling at high feeds and speeds, can introduce tensile residual stresses, which lower fatigue resistance (la Monaca et al., 2021). Conversely, fine finishing techniques like grinding and polishing often induce compressive residual stresses, which enhance fatigue life and resistance to crack initiation (Pramanik et al., 2017). The principles discussed within this section are explored experimentally in Chapters 4-6, where cylindrical test specimens were machined with differing surface finishes (Table 4) to assess their tensile properties.

3.3 The effects of heat on tensile specimen properties

For metallic specimens, factors such as composition, microstructure, and prior heat treatment can significantly impact tensile properties (Wang et al., 2023). For instance, thermal cycling can affect materials' strength, ductility, and toughness, making it crucial to standardise preparation procedures (Dowling et al., 2020). Additionally, the dimensions of the specimen, particularly the cross-sectional area and gauge length, directly influence the calculation of stress and strain (ISO, 2019). Therefore, adherence to standard dimensions prescribed by ASTM and ISO guidelines is critical.

Environmental conditions during testing also play a significant role in the results.

Temperature, in particular, can alter the mechanical behaviour of metals; tensile properties such as Yield Strength and elongation are temperature-dependent (Zou et al., 2023). Thus, while most tests are conducted at room temperature, specific applications may require testing under elevated (Shaheen et al., 2023) or sub-zero temperatures (Balakrishnan et al., 2016) to simulate real-world conditions. Similarly, strain rate — the speed at which the load is applied — can influence properties such as yield strength and ductility (Wang et al., 2017). Metals tested at higher strain rates may exhibit different mechanical responses than those tested at slower rates. Hence, selecting the appropriate strain rate is crucial for obtaining meaningful results.

Cutting fluids are critical in machining, particularly where high temperatures and severe mechanical stresses are prevalent. The primary function of cutting fluids is to cool and lubricate the cutting zone (Zheng Yang et al., 2023). These functions are essential to reduce

friction, control temperature, extend tool life, reduce wear, and improve surface finish (Yan et al., 2016). As a secondary function, cutting fluids have corrosion inhibitors to protect machined surfaces and act as a cleaning operation, which aids in the removal of chips and other debris, ensuring smooth machining operations.

Research highlights the importance of the penetration capability of cutting fluids in improving cooling and lubrication efficiency. Several penetration models, such as the Williams-Tabor model (Dowling et al., 2020), emphasise the role of capillary action in delivering lubricants to the cutting zone. Recent studies have focused on the use of minimum quantity lubrication (MQL) and high-pressure coolant systems to enhance fluid penetration and improve machining efficiency (Said et al., 2019; He et al., 2023). MQL, in particular, has shown promise in reducing cutting forces and tool wear while being environmentally friendly. The effects of coolant use (20L/min versus 0L/min) on the tensile properties of 1.6 μ m cylindrical is assessed both in practice and analytically between Chapters 4-6.



Figure 7-Image of a milling machine using soluble oil coolant. ('Types of CNC Coolants: How to Choose One in Machining?' - WayKen', 2023)

3.4 Theories of simple elastic failure

The strength of materials under complex stress is not generally known, and it is these complicated systems of stress which are most often encountered in practice (Hearn, 1997). Therefore, it is necessary to have some basis for calculating allowable working stresses to predict the behaviour of a material under different loading conditions. This data is key in designing structures and minimising the chance of structural failure (Dowling et al., 2020). Several theories exist in this realm, each seeking to estimate component life under service load conditions.

Rankine's maximum principal-stress criterion posits that yielding or fracture initiates when the largest normal stress matches the uniaxial tensile limit (Qu et al., 2016). While it effectively captures the cleavage-dominated behaviour in brittle solids, it overlooks the crucial influence of shear in metals (Hearn, 1997). Evidence suggests that it should not be used for ductile materials as they do not fail with direct stresses applied, but rather in shear on 45° planes to the specimen's axis.

Guest-Tresca's maximum shear-stress theory enhances this approach by linking failure to when the difference between the largest and smallest principal stresses equals the material's tensile yield strength (Qu et al., 2016). Research suggests this method produces fairly accurate correlations in experimental results, especially in ductile materials in machine design.

Although Guest-Tresca's theory is still widely used for efficiency (Aleksandrova, 2019), the maximum distortion energy theory provides a more reliable basis for estimating complex system response (Hearn, 1997). Often shortened to Von Mises, the theory states that yielding occurs when the maximum distortion energy equals the distortion energy at yielding in a uniaxial tensile test. This theory considers the difference between the principal stresses in the system and is therefore independent of hydrostatic stresses (Dowling et al., 2020). Research suggests that for routine tensile characterisation and subsequent multiaxial design of ductile components, this theory provides the least conservative and most physically justifiable description of initial yielding (Shrivastava et al., 2012). This section directly relates to Chapter 6, where the failure mode of EN8 tensile specimens is assessed and discussed.

3.5 Crack initiation

Crack initiation in EN8 steel often arises from regions with prevalent stress concentration, such as sharp corners, holes, keyways (Fig.8), or other geometric features (Liu et al., 2023). These features significantly elevate local stress, leading to the nucleation of microscopic cracks. Under cyclic loading conditions, fatigue becomes a predominant crack initiation mechanism (Singh et al., 2021). Surface irregularities, machining marks, and material inclusions, such as manganese sulphides or oxide impurities, can act as stress raisers, facilitating early crack formation (Zhu et al., 2023). Additionally, environmental conditions such as moisture, corrosion, or exposure to aggressive chemicals can induce corrosion pits on surfaces, further promoting crack initiation through corrosion fatigue (Manjunath and Surendran, 2013).



Figure 8-Image depicting crack initiation from a keyway. Source:(How does a propeller 'fall off'? - Professional Mariner Forum, 2020)

EN8 steel typically undergoes ductile fracture (Fig.9) under overload or excessive tensile stress. This fracture mode involves void formation and coalescence, producing distinctive dimples on fracture surfaces and significant plastic deformation (Callister and Rethwisch, 2020). Though less common, brittle fracture (Fig.9) is possible under certain conditions, such as low temperatures or surface defects (Kumar et al., 2016), resulting in minimal plastic deformation (Qiu et al., 2014).



Figure 9-Examples of (a)ductile and (b) brittle failure. Source:(Callister and Rethwisch, 2020)

Crack propagation in EN8 steel is significantly affected by various factors, including microstructural characteristics, heat treatment techniques, residual stresses, and specific loading conditions (Callister and Rethwisch, 2020). The ferrite-pearlite microstructure, grain size, and phase distribution directly impact fracture toughness and fatigue resistance; generally, smaller grain sizes improve these properties. Proper heat treatment, such as quenching followed by tempering, can optimise hardness and toughness (Srivastava et al., 2021), thereby decreasing the likelihood of rapid crack growth. Conversely, inadequate heat treatment may lead to excessive brittleness, accelerating crack propagation (Ravindran et al., 2021).

Residual stresses introduced during manufacturing processes- like machining, welding, or heat treatment- also critically influence crack growth behaviour (Callister and Rethwisch, 2020). Tensile residual stresses increase crack propagation rates, while compressive residual

stresses help to inhibit it (Zhang et al., 2002). Additionally, higher cyclic stress amplitude, increased mean stress, or greater loading frequency can accelerate fatigue crack propagation, thereby reducing component lifespan (Dowling et al., 2020).

This section is explored experimentally in Chapters 4-6, where cylindrical test specimens were machined with intentionally introduced circumferential surface defects to assess their tensile properties. Regarding the test specimens' failure mode, the images of the test specimens post-fracture can be viewed in Figs. 35,37,38 and 39.

3.6 Number of test specimens

In tensile testing of metals, research generally recommends testing at least three (Kikuchi et al., 2017; Kumar et al., 2021) to five (Sunder Singh et al., 2020) specimens to ensure statistically reliable results (Chen et al., 2023). Testing multiple specimens is crucial because it helps account for inherent variability in the material, ensuring that the measured mechanical properties accurately represent the material's overall behaviour. By testing several specimens, it becomes possible to detect and exclude outliers that may arise due to material defects, errors in specimen preparation, or anomalies in the testing equipment (Chen et al., 2023). This practice is essential for quality assurance, providing confidence that the material consistently meets the required specifications. These principles are applied experimentally in Chapter 4, where three tensile test specimens over five variables were tested.

3.7 Error in measurement

Every quantitative result includes a measurement uncertainty, which reflects the range of values that can reasonably be assigned to the measurand (Raghavendra and Krishnamurthy, 2013). Reporting this uncertainty is crucial, as it helps readers determine whether observed differences hold statistical and practical significance, aids in comparing results obtained from various sources, and supports conformity assessments (BIPM, 2023).

Uncertainty can stem from several origins, including instrument resolution and drift, environmental factors, operator techniques, reference standards, data-processing algorithms, and model assumptions (Smith, 2016). These elements are integrated to produce a single standard uncertainty for each input parameter, which is then propagated

through the measurement model to calculate the overall combined standard uncertainty of the result

Creating and measuring cylindrical test specimens with a high degree of accuracy is essential for ensuring reliable results (ISO, 2019). This work involves using micrometers, vernier callipers, and surface finish profilometers—each suited to a specific measurement aspect, yet all susceptible to different error types. Understanding how these errors arise and how to minimise them is key to producing consistent and reliable data (Smith, 2016).

Measurement errors generally fall into a few distinct categories. Some are systematic, caused by factors such as calibration drift, environmental effects, or subtle flaws in the setup that introduce the same consistent error (Jiang and Whitehouse, 2012). Others are random, occurring unpredictably due to small vibrations (Holman, 2012), slight variations in hand pressure, or moment-to-moment inconsistencies that no amount of planning can entirely eliminate (Raghavendra and Krishnamurthy, 2013).

There is also the human element, such as misreading a scale through parallax error, misaligning a tool, or even rushing the process. Even the most precise instrument is only as effective as the individual using it (Raghavendra and Krishnamurthy, 2013). Moreover, tools themselves can wear out; for instance, a micrometer with a worn spindle or a calliper with loose jaws will not yield reliable results, regardless of how carefully they are used (Smith, 2016).

Instrument resolution is also significant. A manual vernier calliper, offering a resolution of 0.02 mm (Mitutoyo, 2015), is suitable for quick, general measurements, but it has its limitations, especially when very tight tolerances are involved (Raghavendra and Krishnamurthy, 2013). Micrometers better serve this need, offering much finer resolution, typically 0.01 mm in mechanical types and down to 0.001 mm in digital versions (Mitutoyo, 2015). They are suited for detailed work but require more careful handling (Raghavendra and Krishnamurthy, 2013). Surface finish profilometers go even further, capable of measuring roughness at the micron or sub- micron level—sometimes down to 0.001 μm (Mitutoyo, 2015). This level of sensitivity is crucial when evaluating how a surface might behave in service, especially concerning friction or fatigue (Guo et al., 2024). The principles

discussed here were key to the experimental method of this testing regimen and were used to ensure the geometrical accuracy of the test specimens. These principles are applied within Chapter 4 and expanded upon in Chapter 6.

3.8 Surface microscopy

Surface microscopy plays a crucial role in assessing the microstructural characteristics of metallic specimens which are essential for understanding mechanical behaviours. Typically, EN8 steel consists of a ferrite-pearlite structure in its normalised condition (Sunder Singh et al., 2020b), which can be significantly altered by heat treatments such as annealing, quenching, and tempering (Gopalkrishna et al., 2019). Optical and electron microscopy techniques provide insights into these microstructural changes and their impact on material properties (Moleejane et al., 2014).

The ferrite phase, appearing as light-coloured regions in optical microscopy, provides ductility, while the pearlite phase, which appears as darker regions, enhances strength and hardness. The proportion of these phases directly influences the mechanical properties of EN8 steel (Sanusi et al., 2015). Annealing results in a coarser ferrite-pearlite structure, improving machinability but reducing hardness. Quenching leads to the formation of martensitic structures, increasing hardness and wear resistance, whereas tempering reduces internal stresses and enhances toughness by converting martensite into tempered martensite or bainite (Biswas et al., 2018).

Surface microscopy is also instrumental in identifying defects such as porosity, cracks, and segregation in specimens, which significantly impact mechanical performance and reliability (Moleejane et al., 2014). Inclusions, which are non-metallic particles, weaken mechanical properties and act as stress concentrators (Lambrighs et al., 2010). Micro-cracks, observed under SEM, can lead to premature failure under cyclic loading, while decarburisation, the loss of carbon at the surface, affects hardness and wear resistance (Solgi et al., 2023).

Several microscopy techniques are often employed to analyse metallic specimens' surface morphology and microstructure. Optical microscopy is commonly used for initial microstructural examination, offering information on surface roughness (Smith, 2016), microstructural (Callister and Rethwisch, 2020), and topographical variations (Chen et al., 2023). Samples are prepared through cutting (Fig.19), polishing (Fig.22), and etching with an acidic medium (Nital)(Fig.23) to reveal grain boundaries and phase structures (Balusamy et al., 2024). Scanning Electron Microscopy (SEM) provides high-resolution imaging of the surface morphology and microstructural features of EN8 steel (Prabhu et al., 2022), aiding in detecting inclusions, carbides, and micro-cracks critical for assessing material performance (Moleejane et al., 2014). The fractured tensile test specimens prepared in Chapters 4.1-4.4 are processed using the principles discussed here to prepare samples for microstructural observations. These images and assessment can be viewed in Figs. 42,43,44,45 and 46.

4.Experimental Methodology

4.1 Materials Selection

EN8 steel is an unalloyed medium-carbon steel often chosen for applications that require stronger mechanical properties than mild steel, but without the added cost of alloy steels. Due to its versatility and favourable characteristics, it is widely used in the automotive industry and general engineering. Research shows EN8 is readily machinable, making it easy to process and manufacture (Prabhu et al., 2022). Furthermore, it is available in various forms such as round, square, flat, and plate stock. Additionally, it can be heat-treated—commonly by flame or induction hardening—to achieve a robust surface hardness and moderate wear resistance (Sanusi et al., 2015).

These qualities make EN8 an optimal choice for this project. Its combination of cost-effectiveness, heat treatability, and ease of machining aligns with the study's requirements, ensuring practical feasibility and reliable results.

Key material data is provided in the succeeding tables. Table 1 depicts the results of the chemical composition of the EN8 tested in this case as provided by the supplier (App.1). Table 2 shows the tensile test results for the steel provided during this batch. The manufacturer's Tensile Test was carried out to ISO 6892-1 standards; therefore, this data was used to reference the results in Chapter 5. Finally, Table 3 provides the equivalent material specifications for international standards to allow for modification and experimental repeatability for future research.

Manufacturer:	Hascelik	Country of origin:	Turkey
Mode of manufacture:	Cold-drawn extrusion		
Supplier:	Rapid Metals	Location of purchase:	United Kingdom
Chemical Element	Max (%)	Min (%)	Measured Value (%)
C	0.44	0.36	0.37
Si	0.4	0.1	0.23
Mn	1.0	0.6	0.66
P	0.05	0.0	0.014
S	0.05	0.0	0.028
Cr	0.3	0.0	0.23
Ni	0.3	0.0	0.13
Al	0.3	0.0	0.019
Cu	0.4	0.0	0.16
Mo	0.08	0.0	0.04
V	0.1	0.0	0.005
B	0.0008	0.0000	0.0001
Ti	0.0500	0.0000	0.0088
Sn	0.0000	0.0000	0.0000
Pb	0.0400	0.0000	0.0000
Nb	0.060	0.000	0.001
Cr Mo Ni	0.00	0.00	0.040

Table 1-Mill test certification showing the Chemical Composition of Cold Drawn 8mm EN8 Steel round bar

Measured Property	Max	Min	Manufacturers' tensile test results (EN ISO 6892-1)
Yield Strength (N/mm ²)	N/A	530	621
Tensile Strength (N/mm ²)	N/A	660	786
Elongation (%)	N/A	7	9.9
Reduction in area (%)	99	N/A	N/A

Table 2-Mechanical Properties 8mm EN8 round bar

Standard system	Identifier
BS970	1955 EN8
BS970/PD970	080M40 (1970 onwards)
European Standards	C40, C45, Ck40, Ck45, Cm40, Cm45
Werkstoff Numbers	1.0511, 1.1186, 1.1189
US SAE (AISI):	1039, 1040, 1042, 1043, 1045

Table 3-Equivalent material grades of EN8 for repeatability

4.2 Sample Preparation

The samples in this case (App. 3 and 4) were manufactured using the ISO 6892-1 standard for most dimensional tolerances. However, due to the availability of suitable gripping devices for cylindrical test specimens, it was necessary to modify the transition radius to suit a pattern test specimen supplied by TecQuipment.

All test specimens were manufactured using an XYZ CT52 CNC lathe using Sandvik Carbide tooling under controlled parameters as stipulated in Tables 4,5, and 6.

As justified in section 3.4, three test specimens were tested against five distinct variables as shown in Tables 4,5 and 6, where the testing parameters are outlined. As shown, a total of fifteen test specimens were required. Furthermore, as highlighted in Tables 4 and 5, the tensile results for the 1.6 μm specimens were used twice due to the matching specimen parameters, removing the need to duplicate three more samples.

Average surface roughness (R_a)	Number of specimens	Application of coolant(L/min)
1.6 μm	3	20
3.2 μm	3	20
6.4 μm	3	20

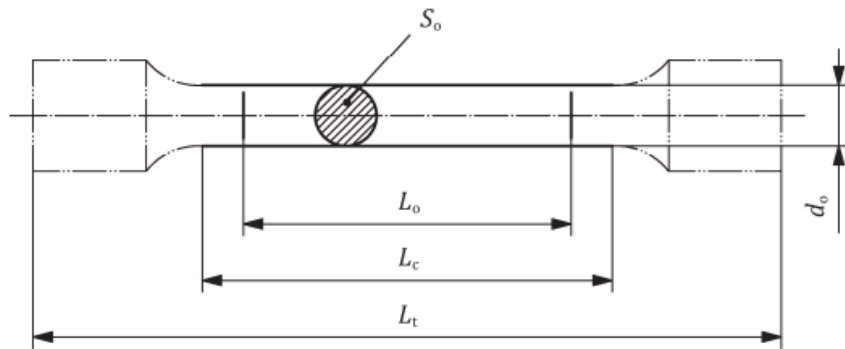
Table 4-Surface roughness parameters

Application of coolant(L/min)	Number of specimens	Average surface roughness (R_a)
20	3	1.6 μm
0	3	1.6 μm

Table 5-Application of coolant parameters

Simulated defect in centre of test piece (Y/N)	Number of specimens	Average surface roughness (R_a)	Application of coolant(L/min)
Y	3	3.2 μm	20

Table 6-Simulated surface defect parameters



Key

- d_o original diameter of the parallel length of a circular test piece
- L_c parallel length
- L_o original gauge length
- L_t total length of test piece
- L_u final gauge length after fracture
- S_o original cross-sectional area of the parallel length

Figure 10-Image of Specimen nomenclature. Source:(ISO 6892, 2019)

4.2.1 Test specimen dimensions, without surface defect

Feature	Nominal Dimension (mm)	Tolerance(mm)	ISO 6892-1 Standard (Y/N)
Gauge diameter (D_o)	5	± 0.03	Y
Gauge Length (L_o)	25	± 0.10	Y
Parallel Length (L_c)	30	± 0.10	Y
Total Length of test specimen (L_T)	40	± 0.20	Y
Transition radius	1.5	± 0.10	N

Table 7-Dimensions of test specimens without surface defect

4.2.2 Test specimen dimensions -with surface defect

Feature	Nominal Dimension (mm)	Tolerance(mm)	ISO 6892-1 Standard (Y/N)
Gauge diameter (D_0)	5	± 0.03	Y
Gauge Length (L_0)	25	± 0.10	Y
Parallel Length (L_C)	30	± 0.10	Y
Total Length of test specimen (L_T)	40	± 0.20	Y
Transition radius	1.5	± 0.10	N
Width of surface defect (W.O.D)	1	± 0.20	N
Defect diameter (D/ϕ)	4.1	± 0.10	N
Radius of notch	0.5mm	N/A	N

Table 8-Dimensions of test specimen with surface defect

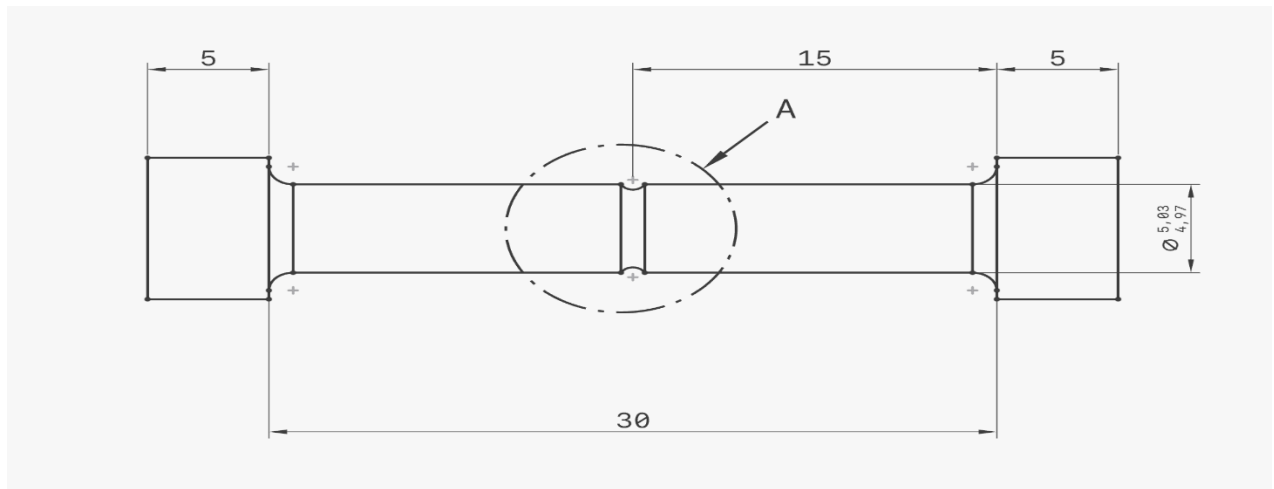


Figure 11-Orthographic drawing depicting notched test specimen

4.2.3 Specimen quality protocols

As shown in Table 9, a quality protocol was established in this case. All test specimens were measured using precision tooling to ensure accuracy, reduce errors and reduce the likelihood of anomalous results. Each tool was checked for calibration before measuring the samples.

In the case of the 0-25mm micrometer, it was indexed to fully closed to ascertain its accuracy (Fig. 12). The 0-position of the main scale corresponded with the 0-position gauge line on the thimble, providing a positive indication of its accuracy.

The digital vernier calliper was calibrated using a similar method; It was completely closed, and the digital scale was zeroed (Fig. 12). This calibration method was repeated after measuring every three specimens for both measuring instruments.

The radius gauges calibration check was more rudimentary, where they were referenced against a master set of female radius gauges.

Finally, the Mitutoyo Surftest surface profilometer (Fig.13) was calibrated against a proprietary reference plate; the calibrated figure was then checked against the digital readout on the machine to confirm its measurement.

Measuring equipment	Manufacturer	Feature to measure	Calibrated to standard
0-25mm outside micrometer	Mitutoyo	Diameters	Y
150mm Digital Vernier calliper	Mitutoyo	Diameters/Lengths	Y
0.5-12mm radius gauges	Moore & Wright	Radii	Y
Digital Surface Profilometer	Mitutoyo Surftest	Average surface roughness	Y

Table 9-Testing protocol of specimens.



Figure 12-0 to 25mm Mitutoyo micrometer and 0-150 Mitutoyo digital vernier with test specimens



Figure 13-Mitutoyo Surftest surface profilometer. Source:(Surface Roughness Measuring Systems | Mitutoyo America Corporation, 2025)

4.2.4 Uncertainty in measurement

The uncertainty for the direct measurement equipment used has been calculated as (ISO, 2019):

$$U_{res} = \frac{R_i}{2}$$

Equation 1-Uncertainty in measurement

Where:

U_{res} = The resolution uncertainty

R_i = The resolution

In terms of calculating the standard uncertainty, it is calculated as (BIPM, 2023):

$$U_{standard} = \frac{(R_i \div 2)}{\sqrt{3}}$$

Equation 2- Standard uncertainty

Measuring equipment	Resolution	Uncertainty $\pm(\mu\text{m})$	Standard uncertainty $\pm(\mu\text{m})$
0-25mm outside micrometer	0.01(mm)	0.005(mm)	0.002887
150mm Digital Vernier calliper	0.01(mm)	0.005(mm)	0.002887
Digital Surface Profilometer	0.01(μm)	0.005(μm)	0.000289

Table 10-Measuring uncertainty calculations of geometrical measuring equipment.

4.3 Recorded dimensions of test specimen geometrical dimensions.

This section shows a record of the critical test specimen geometrical dimensions in tabular format. Each measurement is repeated five times to allow for the calculation of averages necessary for statistical accuracy of tensile results.

4.3.1 Test specimen table nomenclature

Table nomenclature	Description
S/N ^o	Sample number
D_0	Gauge diameter
L_C	Parallel length
D/ ϕ	Notch diameter
W.O.N	Width of notch
R.O.N	Radius of notch
Ra	Average surface roughness

Table 11-Test specimen table nomenclature.

4.3.2 Measurement record of the 6.4 μm specimens

This section shows a test record of critical measurements required for the tensile experiment and results in Sections 5.1.1 and 6.1.1.

6.4 μm Ra							Critical measurement record						
S/No	D_o 1 (mm)	L_C 1 (mm)	D_o 2 (mm)	L_C 2 (mm)	D_o 3 (mm)	L_C 3 (mm)	D_o 4 (mm)	L_C 4 (mm)	D_o 5 (mm)	L_C 5 (mm)	Average D_o (mm)	Average L_C (mm)	Ra (μm)
1	5.03	29.96	5.03	29.95	5.02	29.96	5.03	29.95	5.03	29.96	5.028	29.956	6.404
2	5.03	29.98	5.03	29.98	5.03	29.98	5.04	29.96	5.03	29.97	5.032	29.974	6.408
3	5.04	29.99	5.03	29.98	5.03	29.99	5.02	29.97	5.03	29.99	5.03	29.984	6.410

Table 12-6.4 μm Ra critical measurement record.

4.3.3 Measurement record of the 3.2 μ m specimens

This section shows a test record of critical measurements required for the tensile experiment and results in Sections 5.1.2 and 6.1.2.

3.2 μ m Ra							Critical measurement record						
S/Nº	D_o 1 (mm)	L_C 1 (mm)	D_o 2 (mm)	L_C 2 (mm)	D_o 3 (mm)	L_C 3 (mm)	D_o 4 (mm)	L_C 4 (mm)	D_o 5 (mm)	L_C 5 (mm)	Average D_o (mm)	Average L_C (mm)	Ra (μ m)
1	5	29.92	5.01	29.92	5.01	29.93	5	29.92	5	29.99	5.004	29.936	3.224
2	5.01	29.9	5.01	29.91	5.01	29.91	5.02	29.92	5.01	29.91	5.012	29.91	3.226
3	5.01	29.9	5.02	29.89	5.02	29.91	5.01	29.9	5.01	29.9	5.014	29.9	3.219

Table 13-3.2 μ m Ra specimen critical measurement record.

4.3.4 Measurement record of the 1.6 μ m specimens (with coolant used)

This section shows a test record of critical measurements required for the tensile experiment and results in Sections 5.1.3 and 6.1.3.

1.6 μ m Ra coolant							Critical measurement record						
S/No	D_O 1 (mm)	L_C 1 (mm)	D_O 2 (mm)	L_C 2 (mm)	D_O 3 (mm)	L_C 3 (mm)	D_O 4 (mm)	L_C 4 (mm)	D_O 5 (mm)	L_C 5 (mm)	Average D_O (mm)	Average L_C (mm)	Ra (μ m)
1	5.03	29.93	5.02	29.93	5.03	29.9	5.03	29.92	5.02	29.93	5.026	29.922	1.618
2	5.01	29.93	5	29.93	5.01	29.91	5.01	29.94	5.01	29.94	5.008	29.93	1.624
3	4.99	29.91	4.99	29.9	5	29.91	4.99	29.91	4.99	29.91	4.992	29.908	1.633

Table 14-1.6 Ra specimen (with coolant) critical measurement record.

4.3.5 Measurement record of the 1.6 μ m specimens' (dry turned)

This section shows a test record of critical measurements required for the tensile experiment and results in Sections 5.1.4 and 6.1.4.

1.6 μ m Ra dry turned							Critical measurement record						
S/N ^o	D_o 1 (mm)	L_c 1 (mm)	D_o 2 (mm)	L_c 2 (mm)	D_o 3 (mm)	L_c 3 (mm)	D_o 4 (mm)	L_c 4 (mm)	D_o 5 (mm)	L_c 5 (mm)	Average D_o (mm)	Average L_c (mm)	Ra (μ m)
1	5	29.9	4.99	29.9	4.99	29.89	5	29.9	5	29.9	4.996	29.898	1.632
2	4.99	29.89	4.98	29.91	4.98	29.91	4.98	29.9	4.99	29.9	4.984	29.902	1.621
3	4.98	29.89	4.99	29.91	4.99	29.9	4.98	29.91	4.98	29.91	4.984	29.904	1.642

Table 15-1.6 μ m Ra specimen (no coolant) critical measurement record.

4.3.6 Measurement record of the 3.2µm specimens with surface defect

This section shows a test record of critical measurements required for the tensile experiment and results in Sections 5.1.5 and 6.1.5.

3.2 µm Ra notched specimen						Critical measurement record							
S/Nº	D_0 1 (mm)	L_C 1 (mm)	D_0 2 (mm)	L_C 2 (mm)	D_0 3 (mm)	L_C 3 (mm)	D_0 4 (mm)	L_C 4 (mm)	D_0 5 (mm)	L_C 5 (mm)	Average D_0 (mm)	Average L_C (mm)	Ra (µm)
1	5.03	29.91	5.01	29.9	5.02	29.91	5.03	29.9	5.03	29.91	5.024	29.906	3.240
2	5.02	29.9	5.01	29.91	5.01	29.91	5.01	29.91	5.01	29.91	5.012	29.908	3.220
3	5.02	29.92	5.01	29.91	5.02	29.92	5.02	29.92	5.02	29.92	5.018	29.918	3.248

Table 16-3.2µm Ra defect specimen body dimensions.

3.2µm Ra with defect						The geometrical measurement record continued							
S/Nº	D/ø 1 (mm)	W.O.D 1 (mm)	D/ø2 (mm)	W.O.D 2 (mm)	D/ø3 (mm)	W.O.D 3 (mm)	D/ø 4(mm)	W.O.D 4 (mm)	D/ø5 (mm)	W.O.D 5 (mm)	Average D/ø (mm)	Average W.O.D (mm)	R.O.N(mm)
1	4.10	1.02	4.12	1.02	4.10	1.00	4.11	1.02	4.12	1.01	4.11	1.014	0.5
2	4.14	0.99	4.15	1.01	4.15	1.01	4.14	1.00	4.14	1.01	4.144	1.004	0.5
3	4.12	1.00	4.13	1.02	4.13	1.03	4.13	1.02	4.12	1.01	4.124	1.016	0.5

Table 17-3.2µm Ra defect specimen notch dimensions.

4.4 Formulae used during the experiment.

Symbol	Definition
F _m (kN)	The maximum force a specimen experiences during tensile testing after the beginning of work hardening
R _m (MPa)	Ultimate tensile strength (maximum stress)
F _{p0.2} (kN)	Force at 0.2% plastic strain (conventional yield point)
R _{p0.2} (MPa)	Stress at 0.2% plastic strain (conventional yield strength)
F _f (kN)	Force at fracture (breaking force)
R _f (MPa)	Stress at fracture (breaking stress)
Modulus (GPa)	Young's modulus (elastic modulus)
S _o (mm ²)	Cross-sectional area

Table 18-Tensile testing descriptive nomenclature.

4.4.1 Determining the ultimate tensile strength (UTS)

A definition of UTS is detailed in section 3.2 which can be viewed for further information. The UTS (engineering stress) is calculated as (ISO 6892, 2019):

$$R_m = \frac{F_m}{S_o}$$

Equation 3-Ultimate tensile stress.

Where S_o The cylindrical test specimens are calculated as (ISO, 2019):

$$S_o = \frac{\pi d_o^2}{4}$$

Equation 4-Cross-sectional surface area.

4.4.2 Determining the conventional yield point force

In this case, the 0.2 offset-yield method is used to find the conventional yield point, as the EN8 does not produce a clear transition from the elastic to plastic zone. No arithmetic formula is used as the result was directly derived from the UTM software, which draws a line parallel to the elastic slope, displaced by 0.2 % of the extensometer gauge length. This intersection with the curve gives F_{p0.2}. (ASTM, 2013).

4.4.3 Determining the 0.2% conventional yield stress

The 0.2% yield stress denotes the stress level where a material undergoes a permanent strain of 0.2%. In metals without a clear yield point, it is determined on a stress-strain curve by drawing a line parallel to the initial elastic slope, offset by 0.002 strain. This intersection marks the end of purely elastic behaviour and the start of significant, irreversible plastic deformation (ASTM, 2013).

The 0.2% conventional yield stress is calculated as (ISO, 2019):

$$R_{p0.2} = \frac{F_{p0.2}}{S_o}$$

Equation 5-0.2% Conventional yield stress.

4.4.4 Determining Fracture Force

The force at breaking is the final force recorded at the last data point before the loss of load caused by sample breakage (ISO, 2019). This is an automatically detected condition that requires no further calculation; the value is logged.

4.4.5 Determining Fracture Stress

Fracture stress is the amount of applied (nominal) stress at which a material breaks instead of continuing to deform. It signifies the shift from safe load bearing to catastrophic failure. Engineers determine fracture stress using a material's stress-strain curve, specifically, the point where the curve ends after exceeding the ultimate tensile strength (Dowling et al., 2020).

The Fracture stress is calculated as (ISO, 2019):

$$R_f = \frac{F_f}{S_o}$$

Equation 6-Fracture stress.

4.4.6 Determining elastic modulus

The UTM software automatically calculated the Young's Modulus (E) during the test, though its theoretical basis is defined. Known as the modulus of elasticity, it refers to the ratio of normal (axial) stress to the related normal (axial) strain as the material remains in an elastic state. Essentially, it represents the slope of the linear-elastic portion of a stress–strain curve expressed as:

$$E = \frac{\sigma}{\varepsilon}$$

Where:

$$\sigma = \frac{F}{S_o}$$

$$\varepsilon = \frac{\Delta_L}{L_o}$$

Δ_L = Change in length

Combined, these definitions provide a practical testing formula as:

$$E = \frac{F L_o}{S_o \Delta_L}$$

Equation 7-Youngs Modulus.

4.5 Tensile Test Procedure

Tensile Testing was carried out on cylindrical EN8 steel specimens with a nominal diameter of 5 mm using a Dennison UTM equipped with a 100 kN load cell (Fig.15). The specimens were prepared according to standard geometrical requirements, ensuring a uniform gauge length and surface finish to minimise stress concentrations and provide reliable results.

Before testing, each specimen was carefully measured using a Mitutoyo 0-25mm micrometer and a Mitutoyo 0-150mm digital vernier to determine the initial gauge length and diameter, which were recorded for calculating stress and strain. The specimens were then mounted in split collar grips (Fig.14), specifically selected to securely hold the cylindrical geometry without introducing excessive gripping stress or slippage. The split

collars were tightened uniformly to ensure axial alignment of the specimen within the grips and to minimise bending during loading.



Figure 14- Split collar grip assembly.

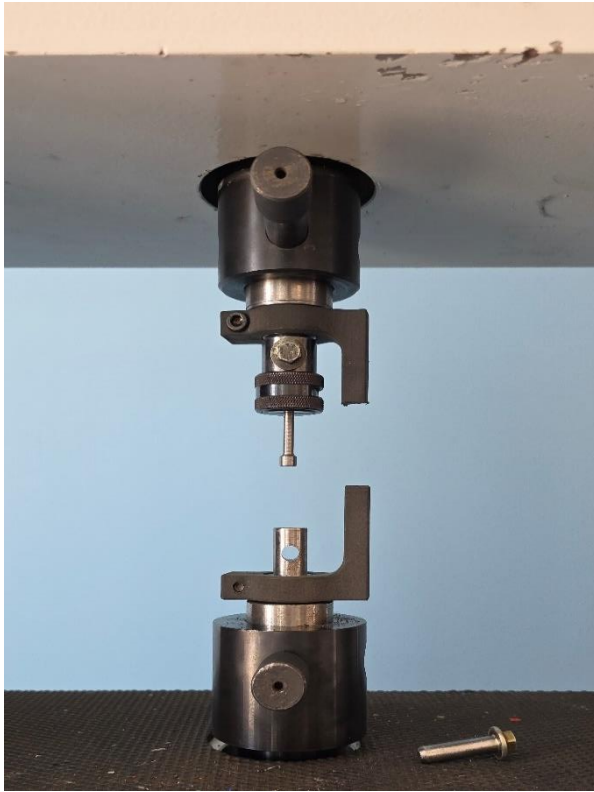


Figure 15-Test specimen mounted in the split collar and assembled fully with the extensometer.

The Dennison Universal Tester was calibrated prior to testing to confirm the accuracy of the load cell. The machine's crosshead was set to move. A uniaxial tensile load was applied at a constant strain rate of 0.00025 S^{-1} as per ISO 6892-1 standard for materials that exhibit yield point phenomenon (ISO, 2019). The Test was conducted until the specimen fractured, and the load-extension and stress-strain curves were recorded. The initial setup ensured that the load applied was purely tensile and that eccentric loading was avoided.



Figure 16-Image of PC with computer tensile testing software running.

Due to the limited gauge range of the Epsilon extensometer available, an additive-manufactured jig was attached (Fig.15) to simulate the gauge length of the tensile specimens. This provided strain measurements during the test's initial elastic and yielding stages. As the test progressed beyond yield and significant plastic deformation began to develop, the extensometer was carefully removed before the final stages of the test to prevent damage to the sensitive instrument during specimen fracture. Subsequent strain measurements were then derived from the machine crosshead displacement and corrected as necessary for system compliance. During testing, load and extension data were recorded continuously until the specimen was fractured. Particular attention was paid to observing the yield point, ultimate tensile strength, fracture force and fracture mode. The stress-strain behaviour was plotted from the recorded data, and key mechanical properties such as Young's modulus, yield strength, and ultimate tensile strength were determined. Upon completion of each test, fractured specimens were retrieved and examined visually and microscopically to assess fracture characteristics. Necking behaviour, surface defects, or features associated with the fracture process were documented as part of the analysis.



Figure 17-Fractured test specimen post-test.

4.5.1 Monitoring of testing environmental conditions

The laboratory's ambient temperature was continuously monitored during each tensile test in strict compliance with ISO 6892-1:2019, which requires that room-temperature tests be conducted within a $(23 \pm 5) ^\circ\text{C}$ range (ISO, 2019). A SwitchBot Smart Thermo-Hygrometer (model W3400010 ; accuracy $\pm 0.2 ^\circ\text{C}$, resolution $0.01 ^\circ\text{C}$) (SHS, 2023) was positioned adjacent to the tensile tester at the level of the grips, ensuring that the temperature reading accurately reflected the material's temperature.

The device recorded the temperature at one-minute intervals from 13:00 to 16:59 on 26 March 2025. Following the tests, the data was transferred from the Switchbot mobile app via Bluetooth and exported to an Excel sheet. This data was used to create the temperature–time graph illustrated in Fig.18. During the monitoring period, the temperature varied from $18.0 ^\circ\text{C}$ to $21.6 ^\circ\text{C}$, with an average of $21.4 ^\circ\text{C}$ and a standard deviation of $0.52 ^\circ\text{C}$.

90% of all readings were between $20.4 ^\circ\text{C}$ and $21.6 ^\circ\text{C}$. Since every measurement comfortably fell within the ISO range ($18 ^\circ\text{C}$ – $28 ^\circ\text{C}$)(ISO, 2019), no interruptions during testing or temperature adjustments were necessary, confirming that the results fully met the standard's environmental-control criteria.

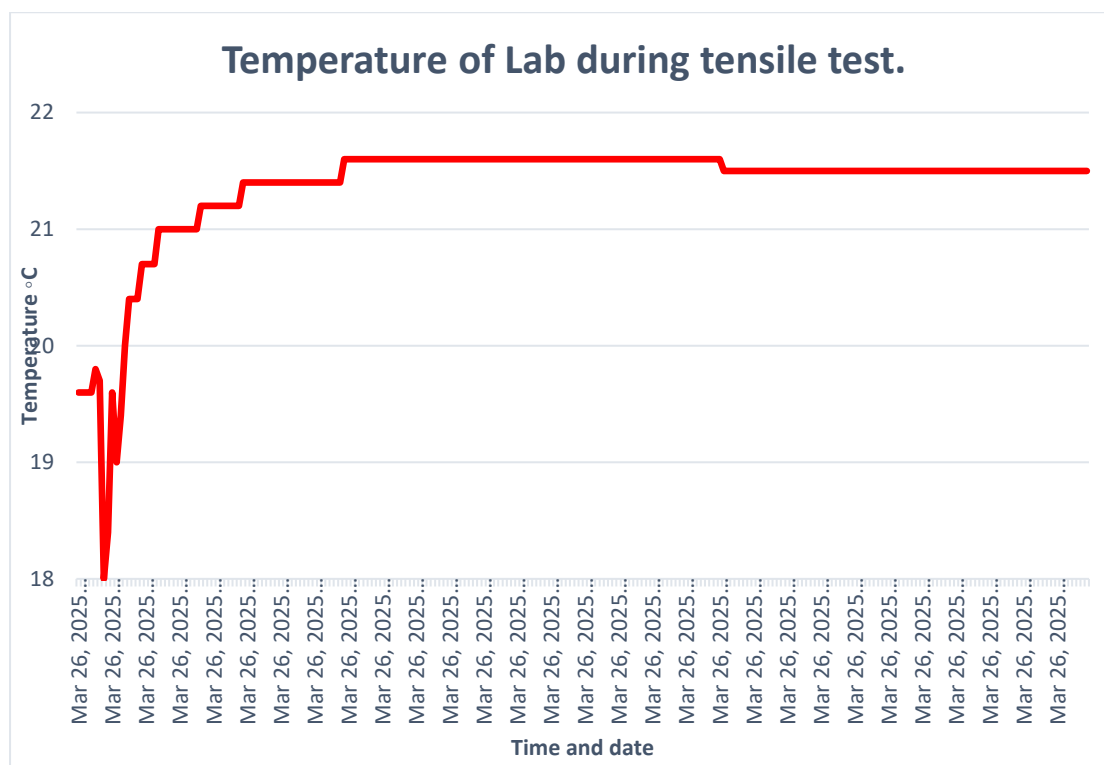


Figure 18- Tensile testing temperature monitoring graph.

4.5 Microscopy Sample Preparation

In preparation for the microstructural observation shown in section 6.2, it was first necessary to process the fractured tensile samples to remove existing scratches, surface defects or imperfections (Oliveira Da Vera et al., 2022).

The preparation of EN8 steel samples for optical microscopy involved a series of precise mounting and polishing steps using Buehler metallographic equipment. Initially, the EN8 specimens were sectioned to dimensions approximately 2.5mm thick using a hacksaw and filed by hand to minimise deformation and thermal damage (Oliveira Da Vera et al., 2022)(Fig.19).



Figure 19-Sample mounted in bench vice in preparation of filing.

Hot mounting was carried out using a Buehler SimpliMet 1000 hot mounting press (Fig. 20), with a phenolic resin (Fig. 21). The mounting cycle was set to 290 bar, with a heating time of three minutes followed by a cooling time of five minutes, after which the mounts were removed once fully cooled. At this point, each mount was scribed for identification.



Figure 20-Buehler SimpliMet 1000 sample moulder in open and closed conditions.

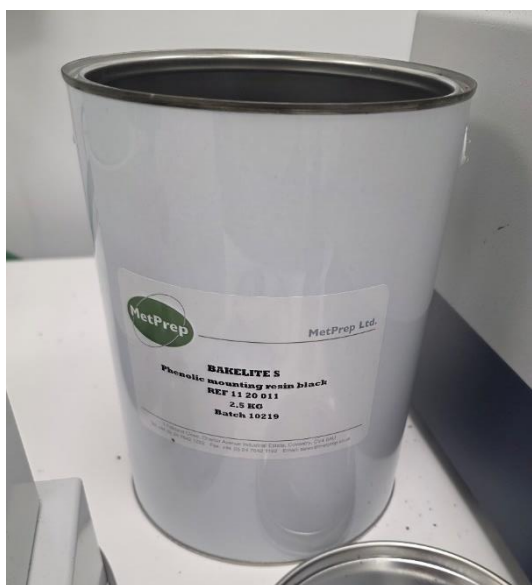


Figure 21-Bakelite phenolic mounting resin.

Grinding was conducted using a Buehler Vector power head Beta grinder-polisher. The initial grinding stage employed 120 grit silicon carbide (SiC) paper (Fig.22) while using a polishing medium to achieve a flat, uniform surface free of tool marks. Progressive grinding steps followed, using 240 SiC paper before a final polish (Fig.22). At each stage, the specimen was rotated by 90° relative to the previous grinding direction to remove scratches from the earlier step effectively.



Figure 22- Buehler power head polishing station.

Following grinding, the specimens were subjected to polishing. Rough polishing was performed using a ChemoMet cloth charged with 9 μm diamond suspension, applying 25 N of pressure and consistent rotation until scratches from the grinding step were eliminated. Final polishing was achieved using Buehler MetaDi diamond suspension (3 μm particle size) to achieve a mirror-like finish.

To reveal the microstructure, an etching step was performed using Nital. Research suggests that a 2-3% concentration is most commonly used for surface microscopy (Obondo and Nyangoye, 2019) (Oliveira Da Vera et al., 2022), although in this case, only 5% was available. The 5% Nital solution comprised 5 mL of nitric acid suspended in 95 mL ethanol (Fig.23). The polished surface of the sample was lightly swabbed with the etchant for ten seconds until the surface turned cloudy, followed immediately by rinsing with isopropanol (Rodriguez-Galeano et al., 2023) and drying with warm air (Obondo and Nyangoye, 2019).

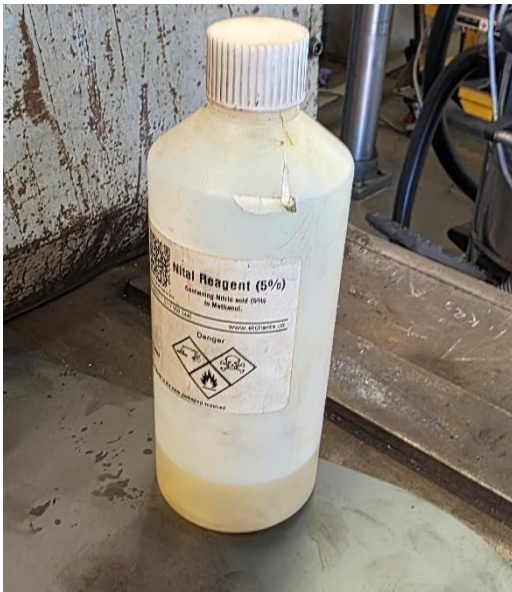


Figure 23-Application of 5% Nital to etch the surface of microscopy samples.

Finally, the prepared samples were examined under a Nikon eclipse optical microscope (Fig.24). A Magnification of 60x was utilised to identify specific microstructural features of interest. Photographs were captured to document the observed structures. The dedicated digital camera system commonly used for capturing micrographs was unavailable, necessitating the use of a conventional digital camera positioned over the eyepiece, although it was not possible to source a suitable C-mount digital camera necessary for capturing detailed micrographs (Nikon, 2025). This required a standard digital camera to be placed over the eyepiece. Although this makeshift approach enabled fundamental photographic documentation, it led to resolution loss and alignment issues, impacting the clarity and accuracy of the images captured.



Figure 24-Nikon eclipse optical microscope.

5. Experimental results

5.1 Tensile testing results

This section presents the results obtained from tensile testing of EN8 test specimens. The tests were conducted to determine key mechanical properties, including ultimate tensile strength, Yield Strength, Young's Modulus and Fracture Force. All specimens were prepared and tested under controlled conditions to ensure the consistency and reliability of data. The results are summarised in tabular and graphical formats between sections 5.1.1 and 5.1.5, allowing for clear comparison and analysis of the mechanical behaviour of the material. To assess the reliability and practical relevance of the tensile testing results, the mean values, the standard deviation (SD), and the coefficient of variation (COV) have been quantified. The SD quantifies the absolute scatter of data (BIPM, 2023) from the mean regarding specimen geometry and tensile properties, providing a measure of repeatability. It was calculated using the STDEV.S function in Excel.

The COV-the SD divided by the mean and expressed as a percentage-normalises this spread, allowing for direct comparison across properties of different magnitudes and against literature data. Presenting both metrics aligns with best practice in ISO 6892-1 (ISO, 2019) and the Guide to the Expression of Uncertainty in Measurement (BIPM, 2023) , which uses the SD and COV to characterise an estimation of testing accuracy.

5.1.1 Tensile test results of 6.4 μm specimens

The test results shown in this section are analysed and discussed in 6.1.1.

6.4 μm test specimens						
Symbol	Sample number 1	Sample number 2	Sample number 3	Average	Standard deviation (%)	C.O.V (%)
Diameter(mm)	5.028	5.032	5.032	5.031	0.002	0.046
cross sectional surface area(mm^2)	19.86	19.89	19.89	19.88	0.018	0.092
Gauge length(mm)	25	25	25	25	0.000	0.000
F _m (kN)	16.3	16.34	14.93	15.85	0.803	5.065
R _m (MPa)	821	822	755	799.33	38.397	4.804
F _{p0.2} (kN)	11.66	14.05	12.23	12.65	1.248	9.868
R _{p0.2} (MPa)	587.11	707.1	618.3	637.5	62.257	9.766
Break (kN)	11.23	12.37	11.84	11.81	0.570	4.830
Break (MPa)	565.59	622.01	595.36	594.17	28.227	4.751
Modulus (GPa)	39	26.22	20.33	28.52	9.545	33.466

Table 19-Tensile Testing results of 6.4 μm Ra specimens.

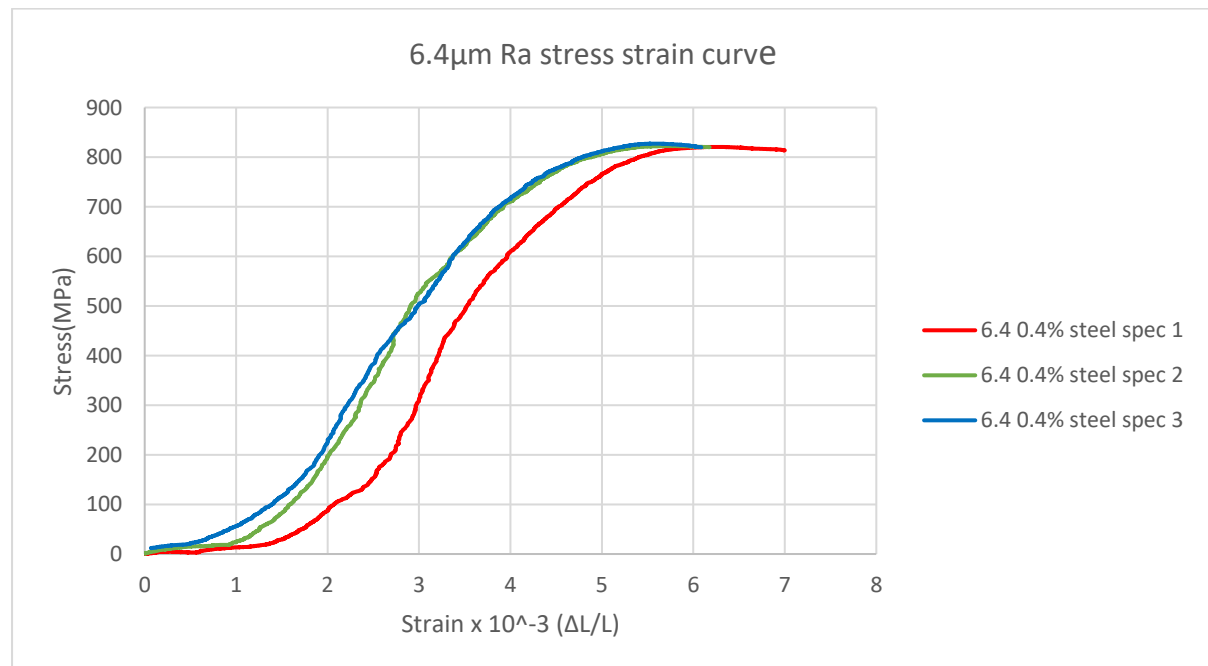


Figure 25-6.4 μm Ra stress-strain curve.

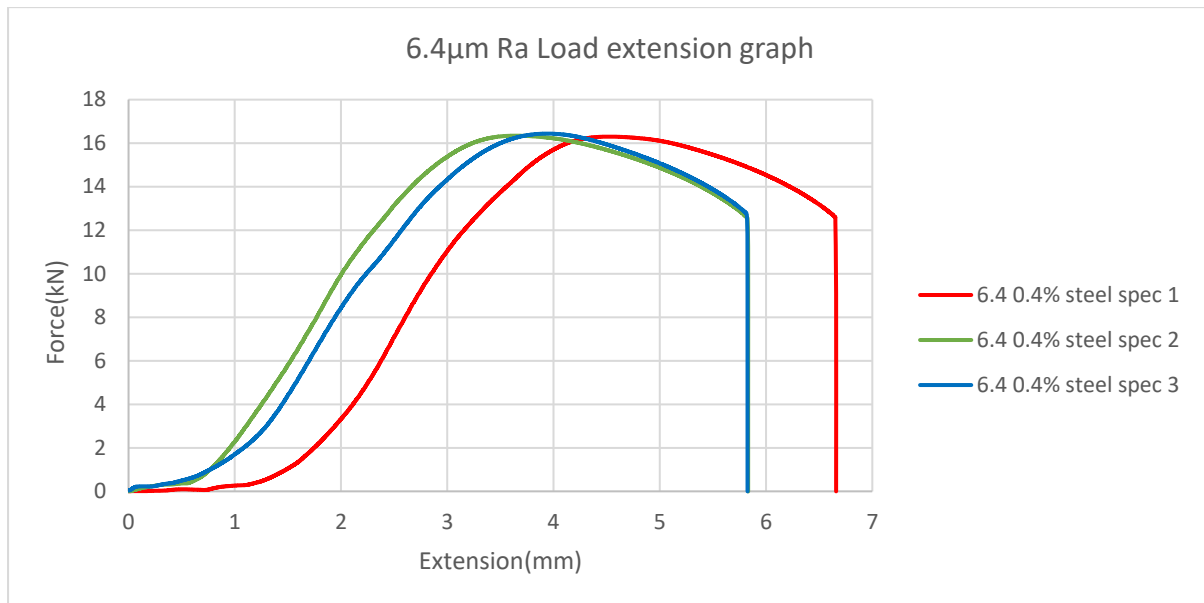


Figure 26-6.4µm Ra load-extension graph.

5.1.2 Tensile test results of 3.2 µm specimens

The test results shown in this section are analysed and discussed in 6.1.2.

3.2 µm test specimens						
Symbol	Sample number 1	Sample number 2	Sample number 3	Average	Standard deviation (%)	COV (%)
Diameter(mm)	5.004	5.012	5.014	5.01	0.005	0.106
cross sectional surface area(mm ²)	19.67	19.73	19.75	19.71	0.042	0.211
Gauge length(mm)	25.00	25.00	25.00	25.00	0.000	0.000
Fm (kN)	16.42	16.43	16.41	16.42	0.010	0.061
Rm (MPa)	835.00	833.00	831.00	833.00	2.000	0.240
Fp0.2 (kN)	13.98	14.05	15.52	14.52	0.870	5.989
Rp0.2 (MPa)	710.73	707.10	785.82	734.55	44.438	6.050
Break (kN)	12.57	11.28	12.51	12.12	0.728	6.007
Break (MPa)	639.16	571.74	633.58	614.80	37.419	6.086
Modulus (GPa)	22.83	26.22	23.78	24.28	1.749	7.202

Table 20-Tensile Testing results of 3.2µm Ra specimens.

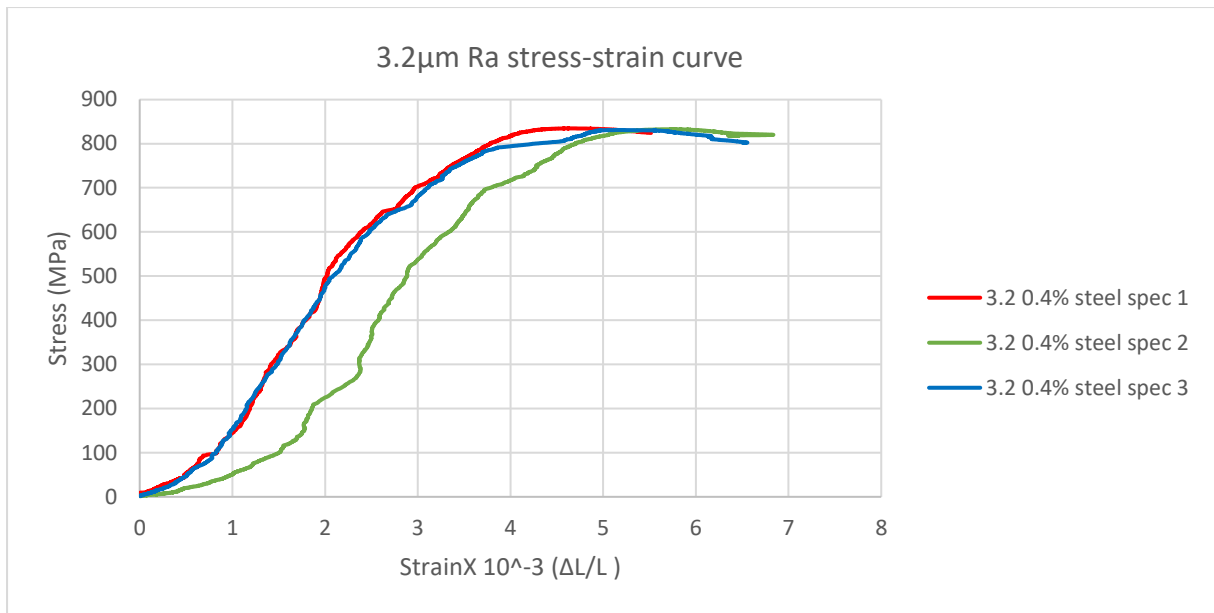


Figure 27-3.2 μ m stress-strain curve.

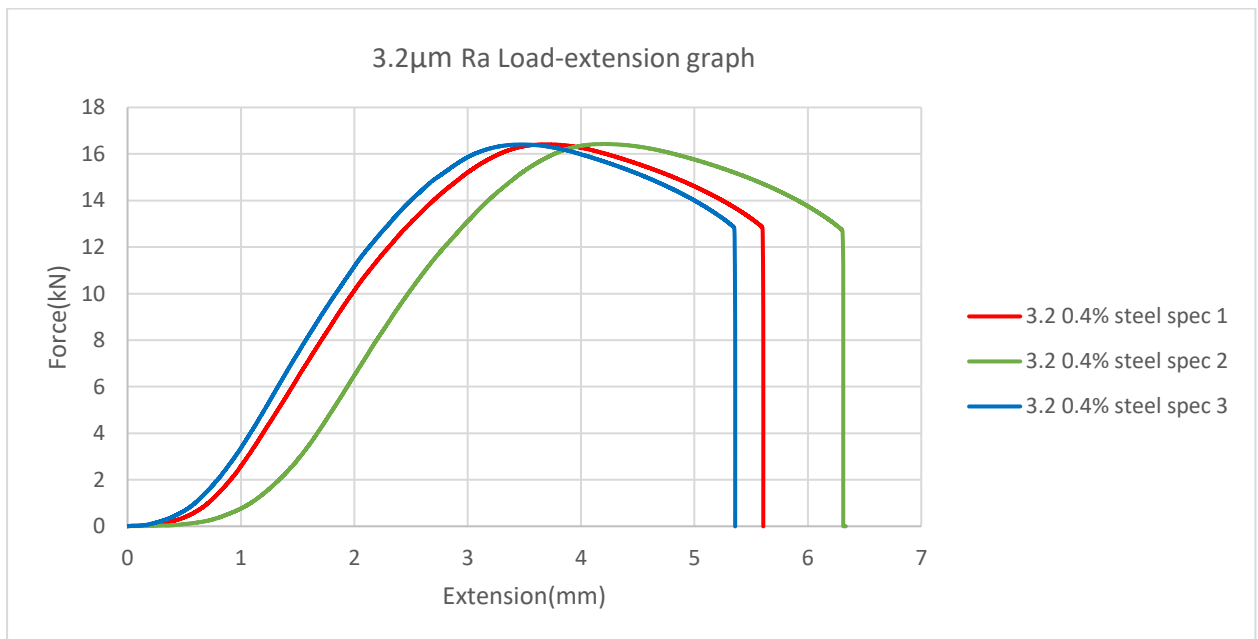


Figure 28-3.2 μ m Ra load-extension graph.

5.1.3 Tensile test results of 1.6 μm (With coolant used) specimens

The test results shown in this section are analysed and discussed in 6.1.3.

1.6 μm (with coolant) test specimens						
Symbol	Sample number 1	Sample number 2	Sample number 3	Average	Standard deviation (%)	COV (%)
Diameter(mm)	5.03	5.01	4.99	5.01	0.017	0.340
cross sectional surface area(mm^2)	19.84	19.70	19.57	19.70	0.134	0.679
Gauge length(mm)	25	25	25	25	0.000	0.000
F _m (kN)	16.38	15.82	15.98	16.06	0.288	1.796
R _m (MPa)	826.00	797.00	805.00	809.33	14.978	1.851
F _{p0.2} (kN)	9.82	9.49	14.84	11.38	2.998	26.345
R _{p0.2} (MPa)	494.96	478.33	747.98	573.76	151.111	26.337
Break (kN)	13.13	12.59	12.38	12.70	0.387	3.047
Break (MPa)	661.80	639.16	632.53	644.57	15.350	2.382
Modulus (GPa)	72.66	18.60	20.29	31.18	30.735	98.564

Table 21-Tensile Testing results of 1.6 μm Ra specimens (with coolant).

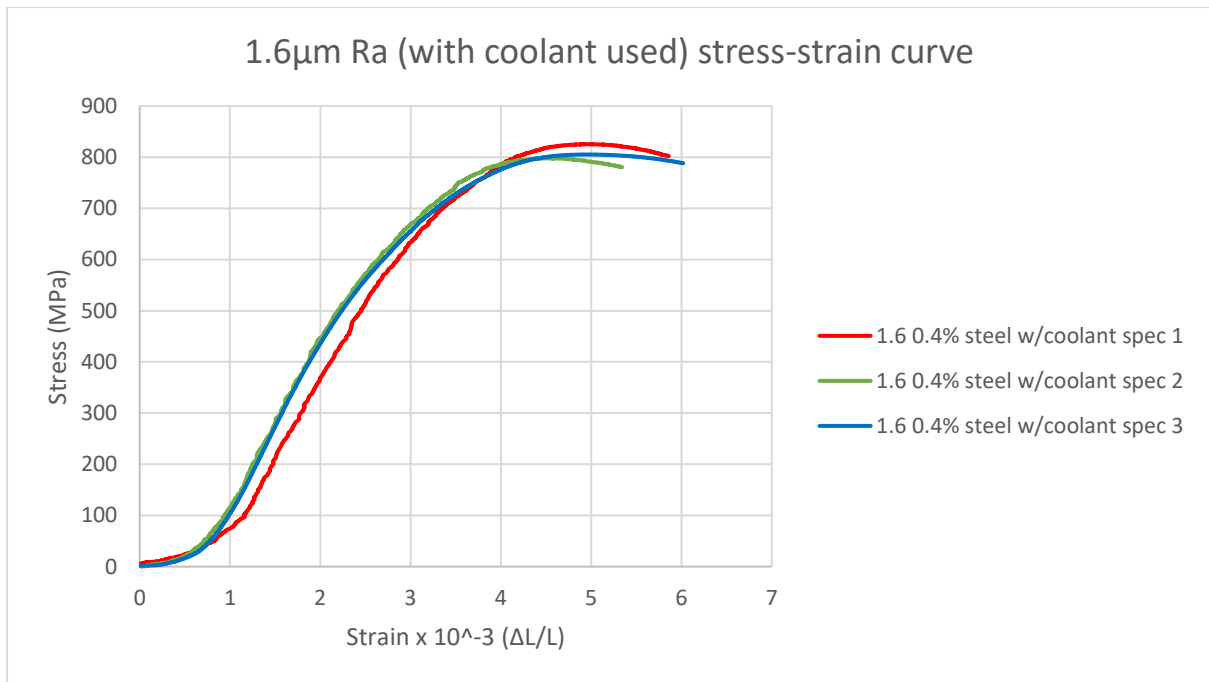


Figure 29-1.6 μ m Ra (with coolant) stress-strain curve.

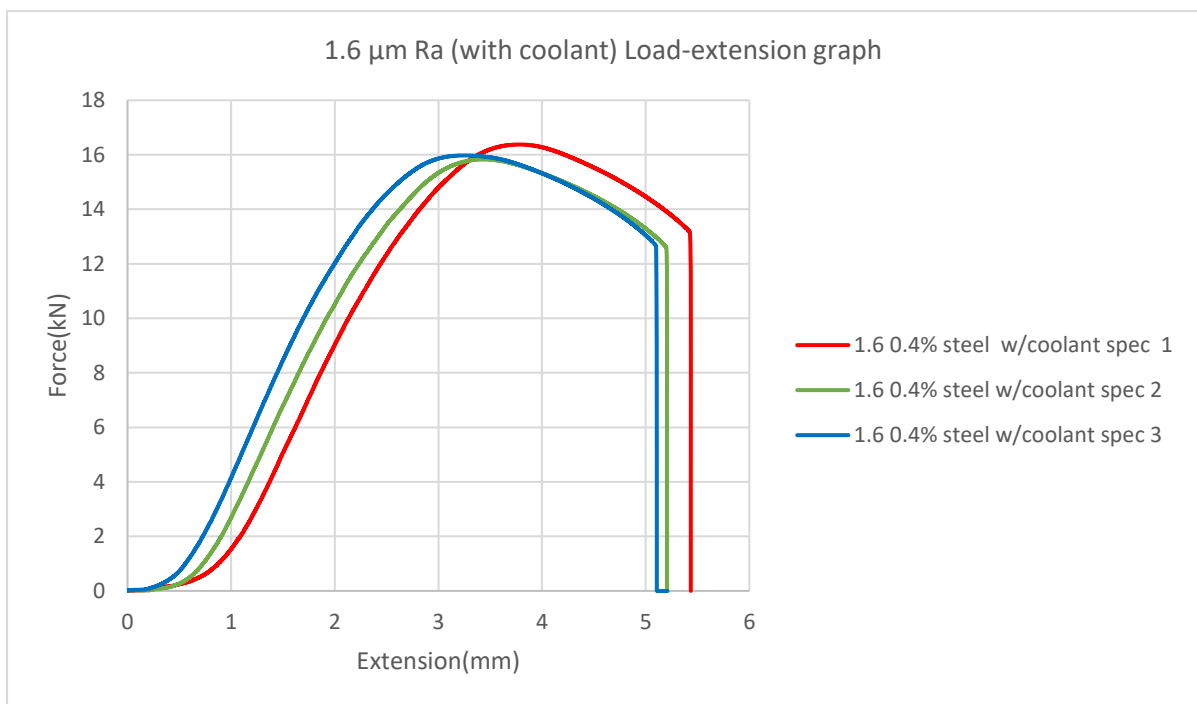


Figure 30-1.6 μ m Ra (with coolant) load extension graph.

5.1.4 Tensile test results of 1.6 μm (no coolant used) specimens

The test results shown in this section are analysed and discussed in 6.1.4.

1.6 μm (no coolant) test specimens						
Symbol	Sample number 1	Sample number 2	Sample number 3	Average	Standard deviation (%)	COV (%)
Diameter (mm)	4.996	4.984	4.984	4.988	0.007	0.139
cross sectional surface area(mm^2)	19.60	19.51	19.51	19.54	0.054	0.278
Gauge length	25	25	25	25	0.000	0.000
F _m (kN)	16.11	16.08	15.98	16.06	0.068	0.424
R _m (MPa)	822	824	819	821.66	2.517	0.306
F _{p0.2} (kN)	10.79	12.24	12.78	11.94	1.029	8.619
R _{p0.2} (MPa)	550.51	627.37	655.05	610.98	54.164	8.865
Break (kN)	12.04	12.25	12.4	12.23	0.181	1.479
Break (MPa)	614.17	627.90	635.59	625.87	10.848	1.733
Modulus (GPa)	32.35	32.44	28.34	31.04	2.342	7.544

Table 22-Tensile Testing results of 1.6 μm Ra specimens (no coolant).

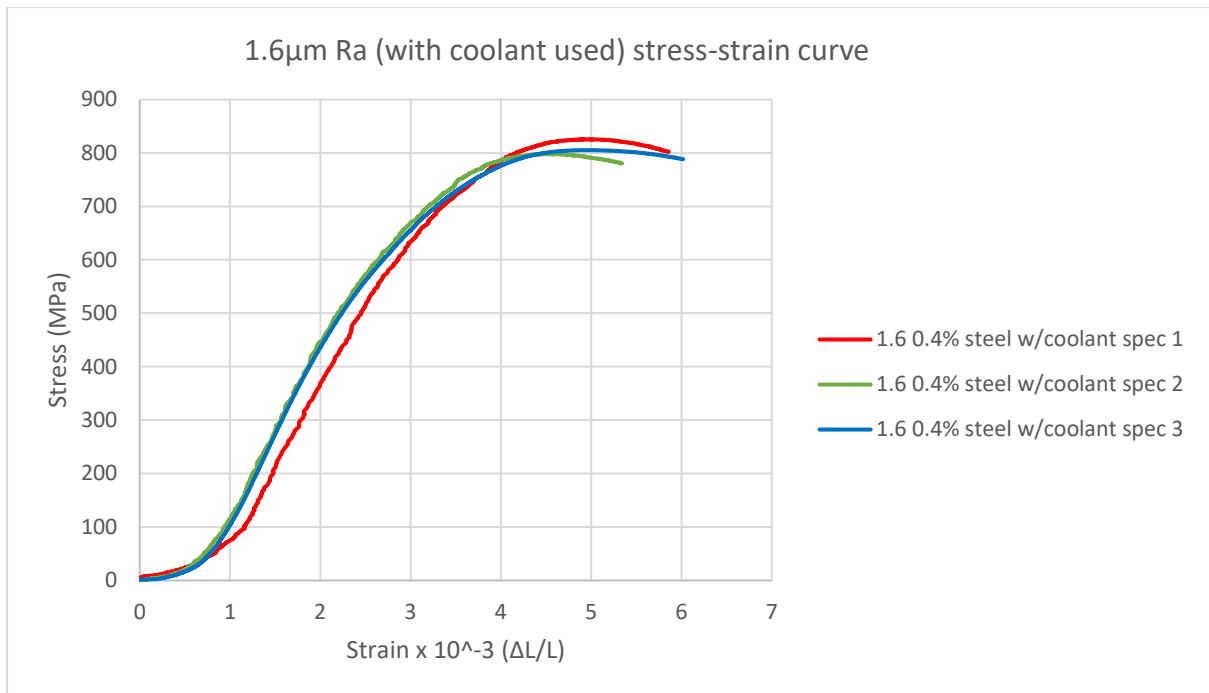


Figure 31-1.6 μ m (no coolant) stress-strain curve.

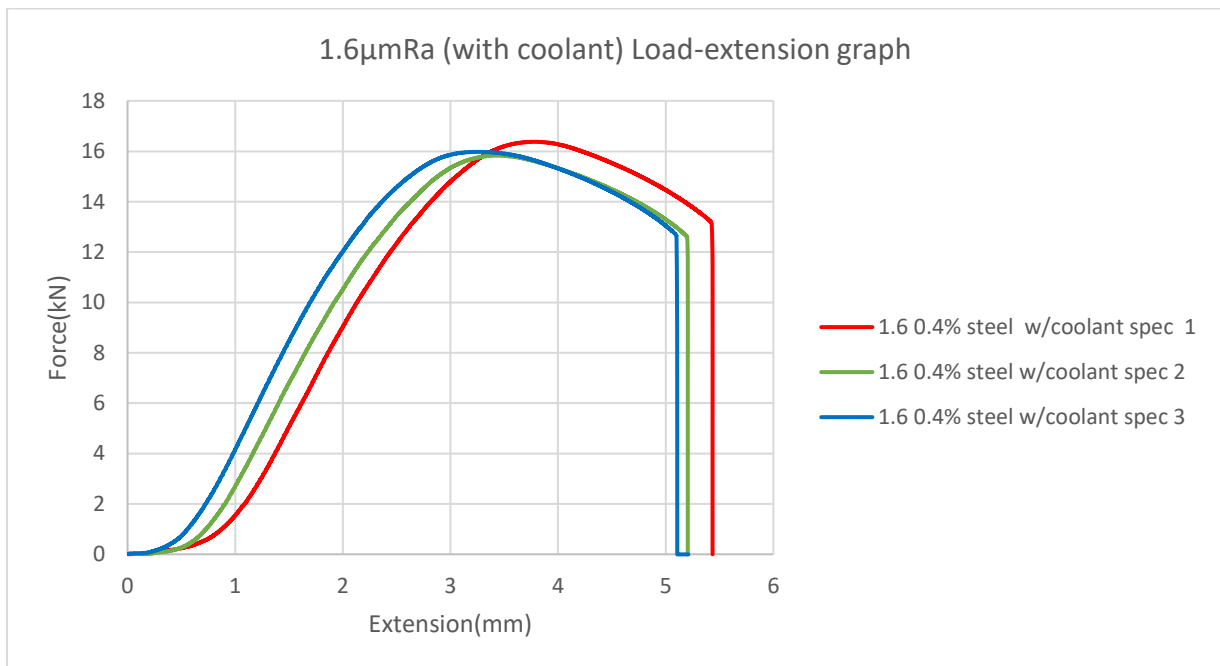


Figure 32-1.6 μ m (no coolant) load extension graph.

5.1.5 Tensile test results of 3.2 μ m Surface defect specimens

The test results shown in this section are analysed and discussed in 6.1.5.

Defect test specimens						
Symbol	Sample number 1	Sample number 2	Sample number 3	Average	Standard deviation (%)	COV (%)
Diameter of body(mm)	5.024	5.012	5.018	5.018	0.006	0.120
Diameter of notch(mm)	4.11	4.144	4.124	4.126	0.017	0.414
cross-sectional surface area of body(mm ²)	19.82	19.73	19.78	19.78	0.047	0.239
cross-sectional surface area of notch(mm ²)	13.27	13.49	13.36	13.37	0.111	0.829
Gauge length(mm)	25.00	25.00	25.00	25.00	0.000	0.000
F _m (kN)	14.43	14.34	14.93	14.57	0.318	2.182
R _m (MPa)	728.00	727.00	755.00	736.67	15.885	2.156
F _{p0.2} (kN)	12.72	12.04	12.23	12.33	0.351	2.846
R _{p0.2} (MPa)	641.78	610.24	618.30	623.44	16.386	2.628
Break (kN)	12.72	14.13	14.66	13.84	1.003	7.245
Break (MPa)	641.65	716.19	741.28	699.82	51.821	7.405
Modulus (GPa)	7.80	28.84	25.86	20.83	11.385	54.657

Table 23-Tensile Testing results of 3.2 μ m with surface defect specimens.

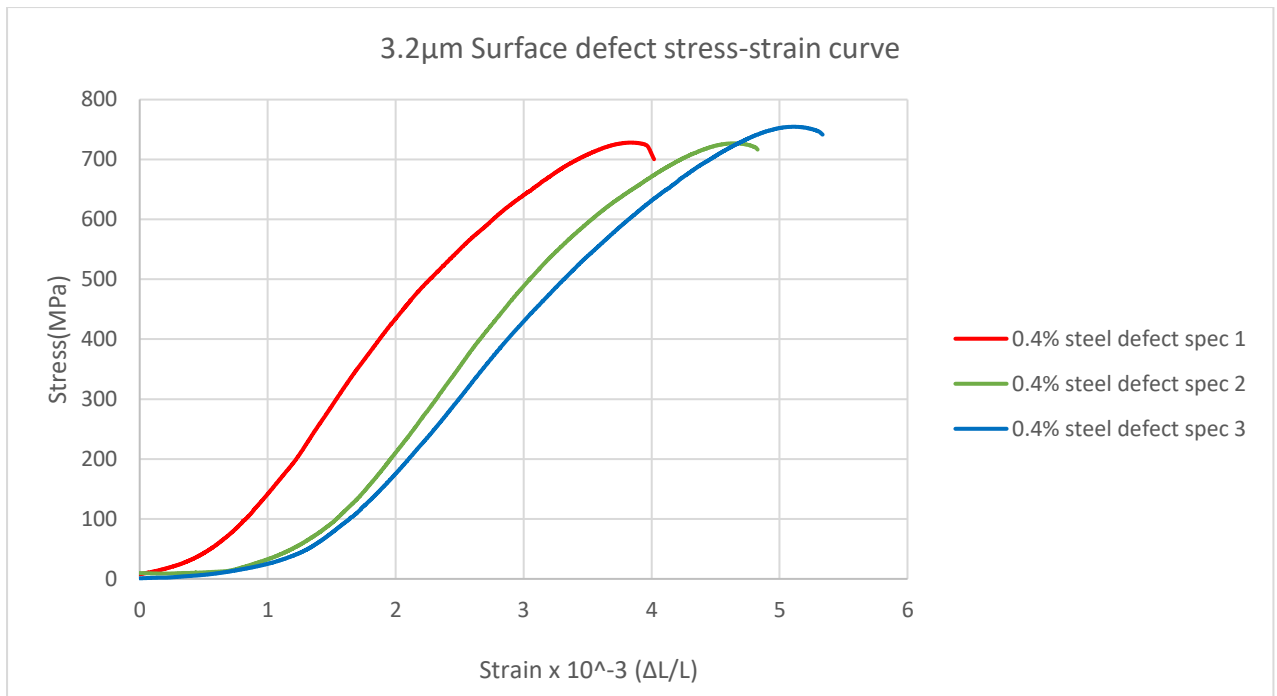


Figure 33-3.2 μ m surface defect stress-strain curve.

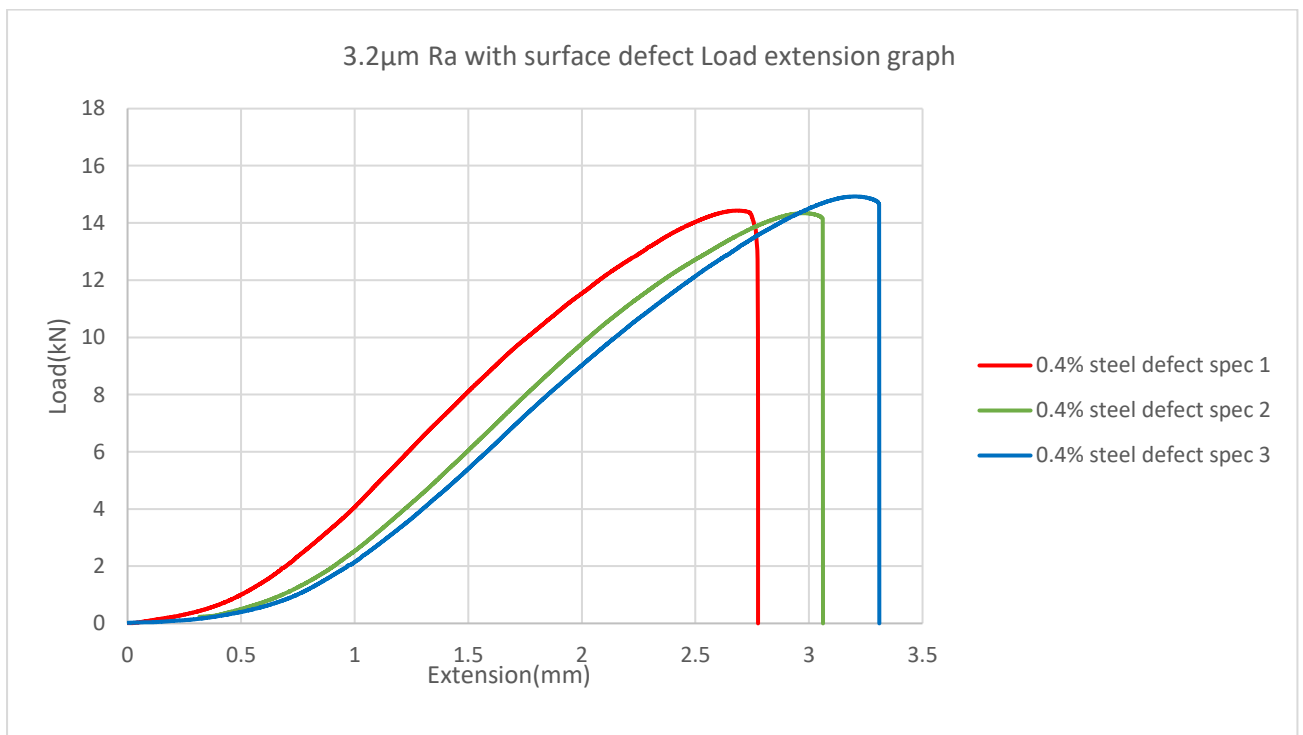


Figure 34-3.2 μ m surface defect load extension.

6. Analysis

6.1 Tensile test data analysis

This section evaluates how surface finish, coolant application and deliberately introduced flaws influence the tensile response of EN8 steel. Five specimen groups were examined, whose controlled variables were machining parameters and a machined surface defect in the final case.

6.1.1 Analysis of 6.4 μm test specimen data

As shown in the data from 5.1.1, tensile tests were conducted on specimens with a surface roughness of 6.4 μm Ra, each machined to a gauge length of 25 mm and an average diameter of 5.031 mm (resulting in a cross-sectional area of approximately 19.88 mm²). The COV was minimal- the maximum SD in both diameter and area was less than 0.05% (Table 19), indicating that any differences in mechanical response are likely due to the material itself rather than the geometry of the specimens. The average maximum force (F_m) recorded was 15.85 kN, corresponding to an average ultimate tensile strength (R_m) of 799 MPa (Table 19). The consistency of F_m and R_m values across the samples was uniform, with samples 1 and 2 correlating closely, suggesting good uniformity in tensile performance under peak loading conditions. The 0.2% proof stress ($R_{p0.2}$), representing the yield strength, averaged 637.5 MPa. This value is slightly lower than UTS, with variation among samples, especially sample 1, which had the lowest $R_{p0.2}$ of 587.11 MPa, possibly caused by inconsistencies in the material structure (Callister and Rethwisch, 2020) or instrumental errors (Womack, 2024). The average force and stress at fracture were 11.81 kN and 594.17 MPa, indicating substantial ductility as the material retained load-bearing capacity after yielding, a finding supported by the ductile failure shown in Fig.35. An unexpected observation was the low modulus of elasticity, averaging 28.52 GPa and a value scatter exceeding 30 %, well below the expected 200 GPa for steels (Chen et al., 2016), (MatWeb, 2025). This may be due to strain measurement inaccuracies, possibly caused by slippage from the sample bedding into the grips (Womack, 2024). There is some evidence to support this suggestion (Figs. 27 and 28) as the applied stress and force do not increase in an exponential manner at the start of the test, as observed in other published literature (Abed et al., 2018), (Zarroug et al., 2003). Further evidence points to instrumental error (Womack,

2024) caused by the removal of the extensometer during testing, or more likely due to the use of the Gauge simulating attachment (shown in Fig. 15) affecting the results, so reported modulus values should be interpreted with caution.



Figure 35-Image depicting the ductile failure mode of the 6.4 μ m specimen.

6.1.2 Analysis of 3.2 μm test specimen data

As shown in the data from 5.1.2, the tensile response of the 3.2 Ra specimens suggests that the surface finish may exert a measurable influence on the tensile performance of EN8. All three samples were machined to a nominal gauge length of 25 mm and an average diameter of 5.01 mm, giving a mean cross-sectional area of 19.71 mm² with less than 0.2 % geometric scatter.

Load–extension data indicates good reproducibility in the plastic region, the ultimate load is clustered around 16.42 ± 0.01 kN, which corresponds to an average UTS of 833 MPa and a COV of less than 0.3% (Table 19). This strength is approximately 4% greater than the rougher 6.4 Ra batch tested under the same conditions.

A more pronounced effect is observed in the 0.2 % offset yield strength, $R_{p0.2}$. The 3.2 Ra specimens produced a mean yield of 735 MPa (Table 19), approximately 15 % higher than the 6.4 Ra samples, and did so with markedly improved repeatability.

Fracture behaviour mirrored the improvements in earlier stages of deformation, indicating a ductile fracture (Fig. 36). Mean break stress increased to 615 MPa, and the stress drop from UTS to fracture remained steady, signifying that failure was governed by necking rather than premature surface crack initiation (Fig.27).

One anomaly common to both sample sets is the unrealistically low elastic modulus obtained from the initial slope of the stress–strain curves (24 ± 2 GPa) as observed in 6.1.1 (Chen et al., 2016). It is posed that the error may again be instrumental.

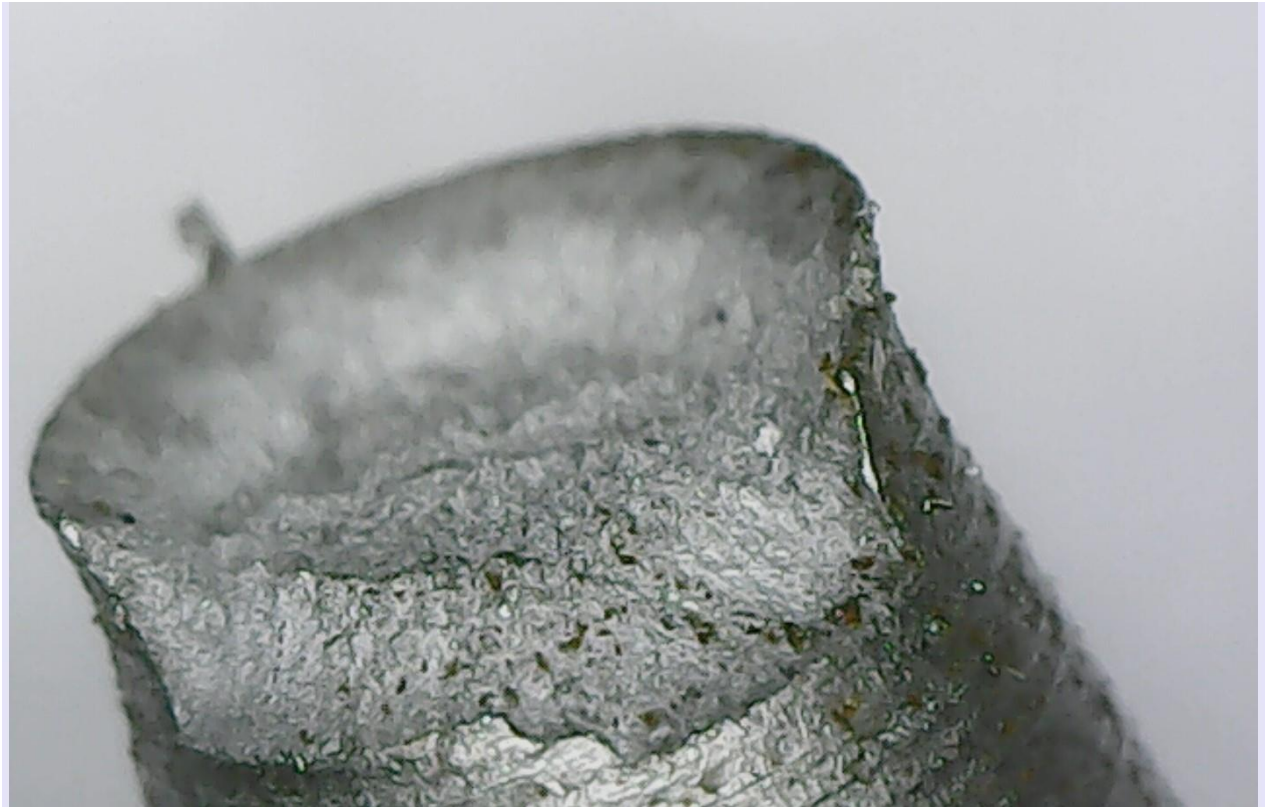


Figure 36-Image depicting the ductile failure mode of 3.2 μ m specimen.

6.1.3 Analysis of 1.6 μ m Ra (with coolant used) test specimen data

The data from 5.1.3 serves as the third data set where the 1.6 Ra (with coolant used) specimens are assessed. All three samples were machined to the same 25 mm gauge length utilised earlier; their average diameter was measured at 5.01 mm, and the cross-sectional area averaged 19.70 mm², with less than 0.3 % geometric variation (Table 21). This consistency ensures that any differences in strength arise from the material or surface conditions, not from dimensional discrepancies. The ultimate tensile strength (UTS) was highly consistent, with the average maximum load h 16.06 kN, translating to an average UTS of 809 MPa (Table 21). The value variations were under 2% for both measures, only slightly higher than the variation noted for the smoother 3.2 Ra material. Compared to the rough-machined 6.4 Ra specimens, the 1.6Ra improves UTS by about 1 % (809 MPa versus 799 MPa) but falls short of the 833 MPa achieved at 3.2 Ra, indicating that the beneficial effect of decreased roughness may plateau past this threshold.

In terms of yield strength, while specimen 3 reported a yield of 748 MPa (in line with the 3.2 Ra batch), specimens 1 and 2 yielded at just 495 MPa and 478 MPa (Table 21). The resulting mean of 574 MPa shows a 26 % coefficient of variation, far larger than the scatter

in UTS. As with the earlier data-sets (6.1.1 and 6.1.2), part of this must be attributed to instrumentation (Womack, 2024). The elastic modulus extracted from the initial slope fluctuated from 72 GPa in specimen one to ≈ 20 GPa in the other two, demonstrating that grip compliance or extensometer seating remained unresolved during testing. Despite this yield anomaly, fracture behaviour remained consistent. Break loads averaged 12.7 kN, producing an average fracture stress of 645 MPa—the highest of the three surface states tested. while the stress drop from UTS to failure was gradual (Fig.29), again signifying a ductile failure (Fig.37).



Figure 37-Image depicting the ductile failure mode of a 1.6 μ m specimen (with coolant).

6.1.4 Analysis of 1.6 μ m Ra (no coolant used) test specimen data

The data from 5.1.4 shows specimens with a dry-turned surface roughness of 1.6 μ m Ra, offering an intermediate finish between the rough 6.4 μ m Ra and the fine 3.2 μ m Ra conditions examined earlier. Regarding dimensional control, the average diameter was 4.988 mm (± 0.14 % scatter) and the cross-sectional area 19.54 mm² (± 0.28 %) (Table 22). In the plastic region, the material displayed very high and repeatable strength again. Peak loads converged at 16.06 kN, yielding an average ultimate tensile strength (UTS) of 822 MPa with a coefficient of variation of just 0.25 %—virtually identical to the finish-turned 3.2 Ra

batch and roughly 3 % above the rough-turned 6.4 Ra specimens. In contrast, the 0.2 % offset yield strength exhibited greater variation. $R_p 0.2$ in the specimens ranged from 551–655 MPa, averaging 611 MPa with a 9% C.O.V (Table 22). Although this dispersion is markedly smaller than the 26 % measured for the coolant-turned 1.6 Ra series, it still exceeds that of UTS.

Fracture behaviour was similarly consistent: break loads averaged 12.23 kN, corresponding to a fracture stress of 626 MPa. The failure mode mirrored earlier tests, again exhibiting a ductile failure (Fig.36).

As with preceding batches, the elastic modulus derived from the initial slope of the stress–strain curve remained unrealistically low (31 ± 2 GPa). The 0.2 % offset method relies on this slope (ASTM, 2013), grip compliance or extensometer seating error almost certainly biased the reported yield values (Womack, 2024).

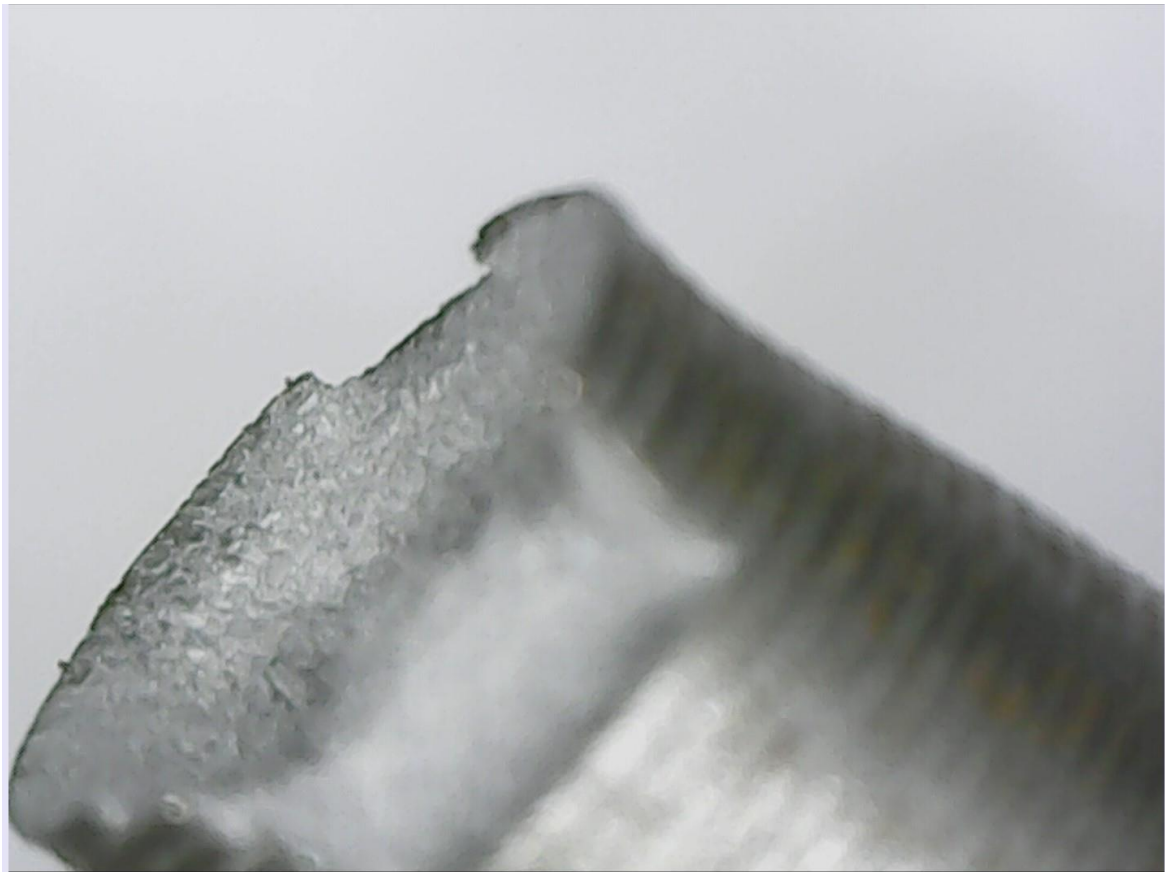


Figure 38-Image depicting the ductile failure mode of 1.6 μ m specimen (dry turned).

6.1.5 Analysis of 3.2 μ m Ra Surface defect test specimen data

As shown in the data in 5.1.5, introducing a controlled surface defect had a distinct and measurable effect on the steel's tensile performance. The “defect” specimens were machined to match the nominal geometry of the earlier batches (25 mm gauge length, approximately 5 mm at the major diameter and 4mm on the notch diameter), with minimal dimensional variability (± 0.12 % on diameter, ± 0.24 % on cross-sectional area), ensuring that any mechanical differences stemmed from the defects rather than size variations. The average ultimate load decreased from around 16 kN in the defect-free 1.6 Ra dry-turned material to 14.6 kN, resulting in an ultimate tensile strength (UTS) of 737 MPa, which marks a roughly 10 % reduction compared to the flawless benchmark. Conversely, the 0.2 % offset yield strength remained virtually unchanged at 623 MPa. Fracture behaviour highlights this reduction in strain-hardening capacity: break stresses averaged 700 MPa and occurred only about 5 % below the UTS, suggesting a brittle failure (Figs.39,40 and 41). Research indicates that this is due to the plastic deformation occurring purely at the zone of the defect resulting in minimal extension (Hearn, 1997). Essentially, the pre-machined imperfections serve as crack initiators that significantly limit the post-yield deformation energy the material can withstand (Dowling et al., 2020). One experimental caveat persists across all batches(6.1.1,6.1.2,6.1.3, and 6.1.4): the elastic modulus extracted from the initial slopes is unrealistically low, 7–29 GPa (Chen et al., 2016).

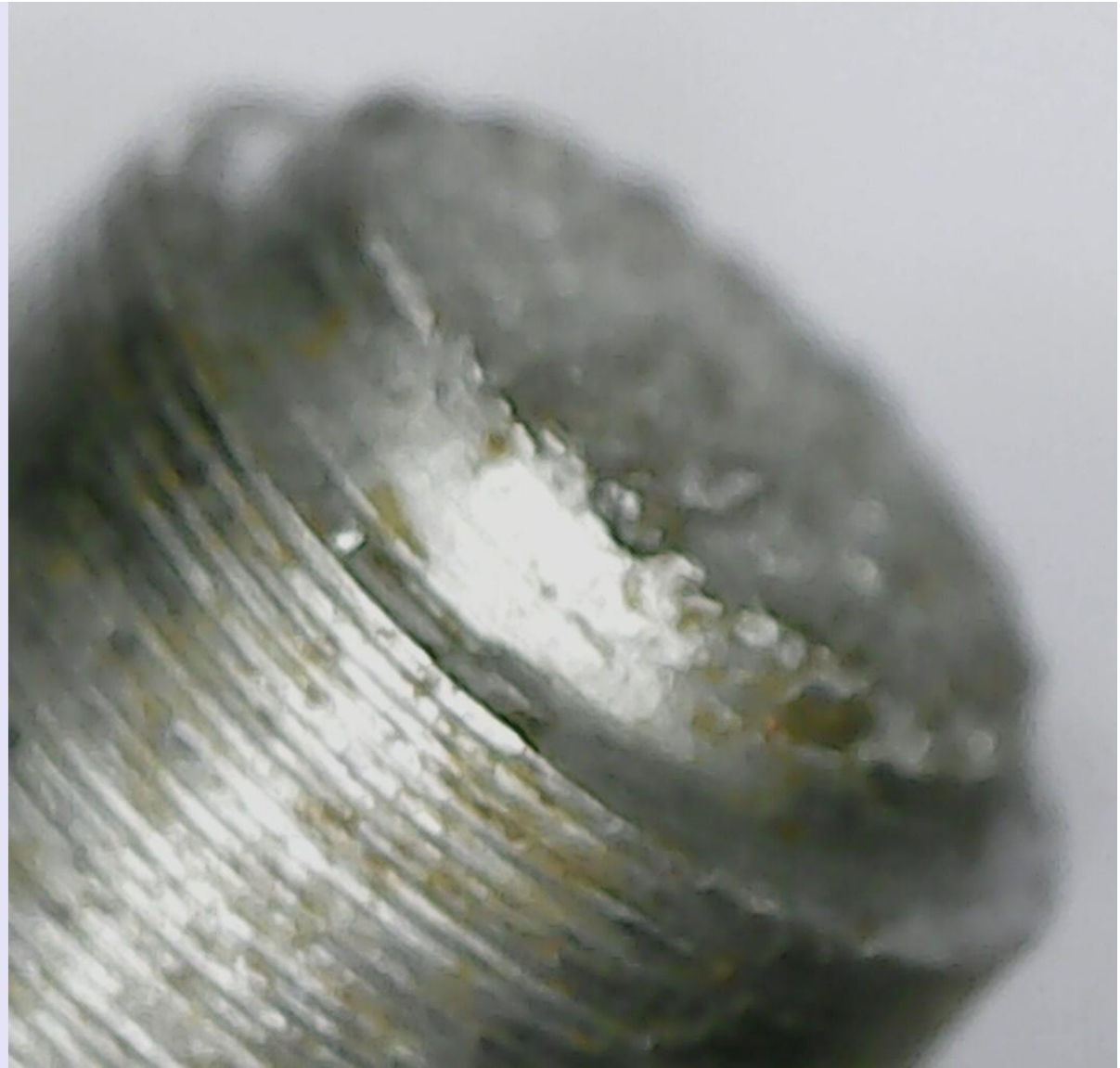


Figure 39-Image depicting the failure mode of 3.2 μ m notched specimen.



Figure 40-3.2 μ m notched specimens showing minimal plastic deformation.



Figure 41-A side-by-side comparison of conventional ductile failure with the failed notch specimens.

6.1.6 Analysis of all testing variables versus the manufacturer's test record

It was noted that the results from all analyses (6.1.1-6.1.5) compared with the mill Tensile Test record shown Table 2, did not fully correlate. The 6.4 and 3.2 samples exceeded the manufacturer's, with the Yield Strength increasing by $\approx 18\%$ and Tensile Strength by 1-6% respectively. The surface defect specimens underperform in ultimate strength, coming in about 6 % short (likely due to the notch in the specimen), although their yield is essentially on par with the manufacturer's figure.

The 1.6 (with coolant) specimens carry about 8 % less yield strength but still exceed the ultimate target by $\approx 3\%$. Finally, the 1.6 (dry turned) specimens were only marginally below the quoted Yield Strength and 2% stronger in UTS. Due to the instrumental errors stated between (6.1.1-6.1.5), it is recommended that further investigation is required to confirm whether these variations are accurate.

6.2 Microscopy analysis

This section presents the surface microscopy results of the EN8 test specimens, obtained using an optical microscope. The analysis examined microstructural characteristics and potential surface defects. Images were captured at 60x magnification to provide a detailed visual assessment of the specimen surfaces before and after tensile testing. The observations contribute to understanding the material's surface condition and any deformation or damage resulting from mechanical loading.

Observations were made of the mounted samples to assess their microstructure and examine whether they exhibited different grain structures. All five sample sets did not appear to exhibit drastic differences in the microstructure.

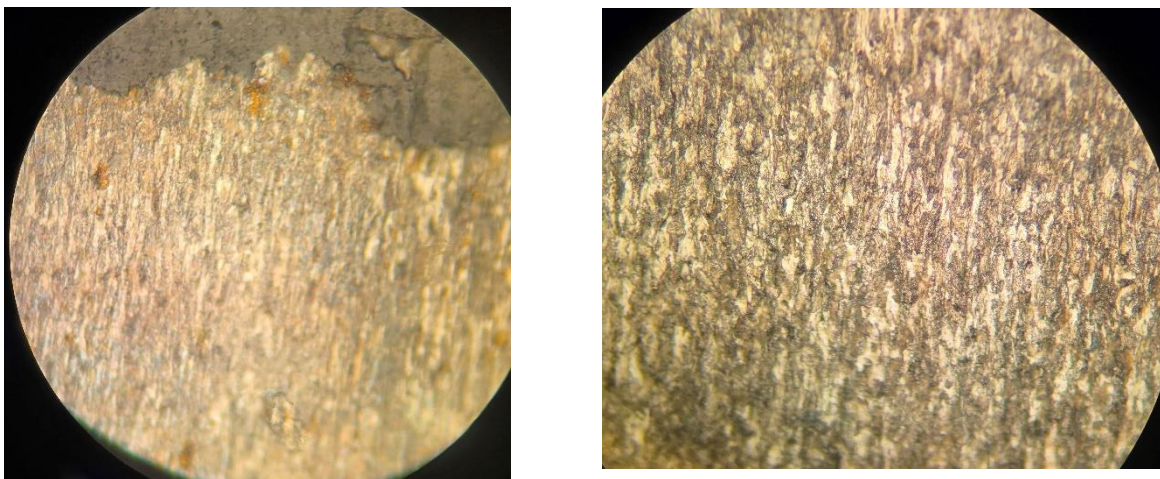


Figure 42- Surface structure of 6.4 μ m Ra specimen.

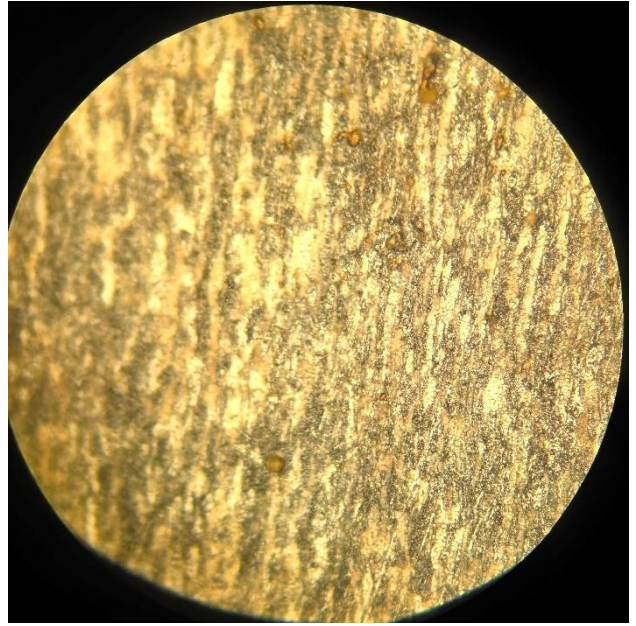
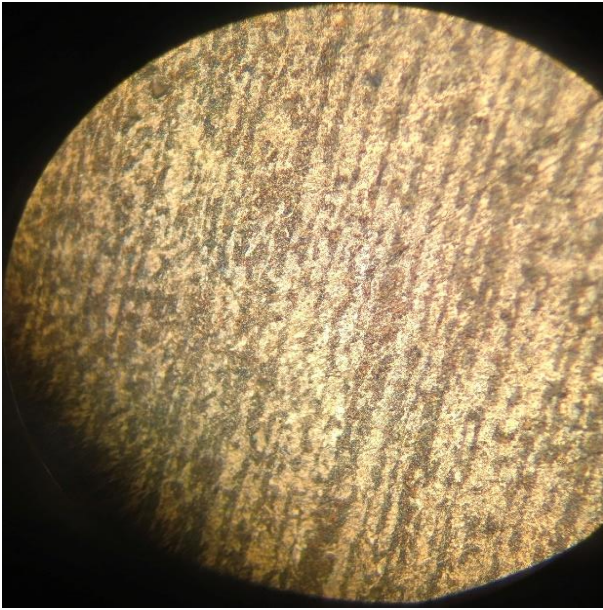


Figure 43-Surface structure of 3.2 μm Ra specimen.

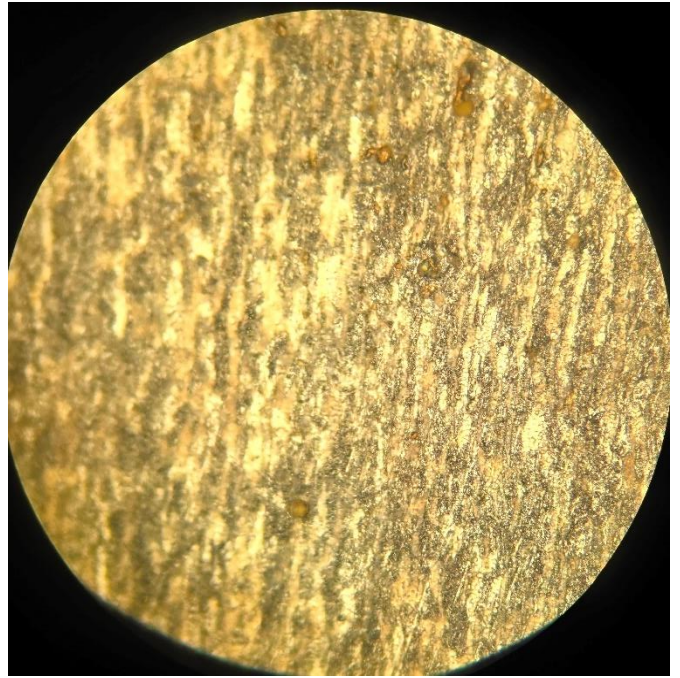
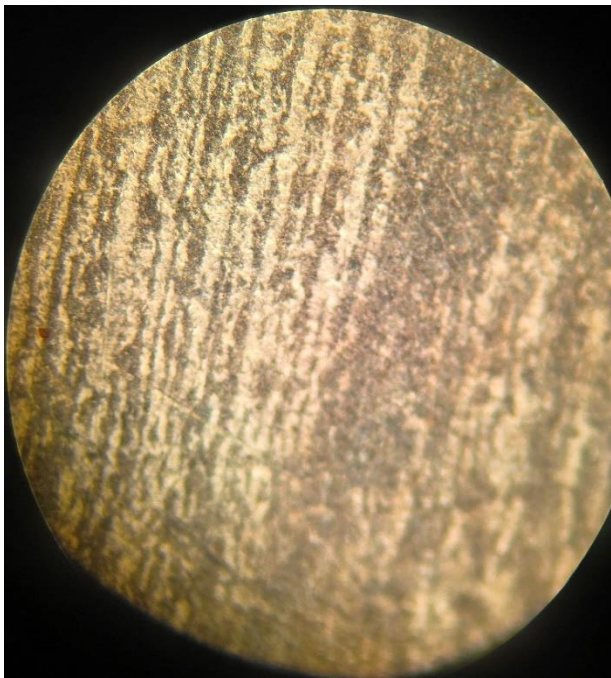


Figure 44-Surface structure of 1.6 μm Ra specimen(with coolant).

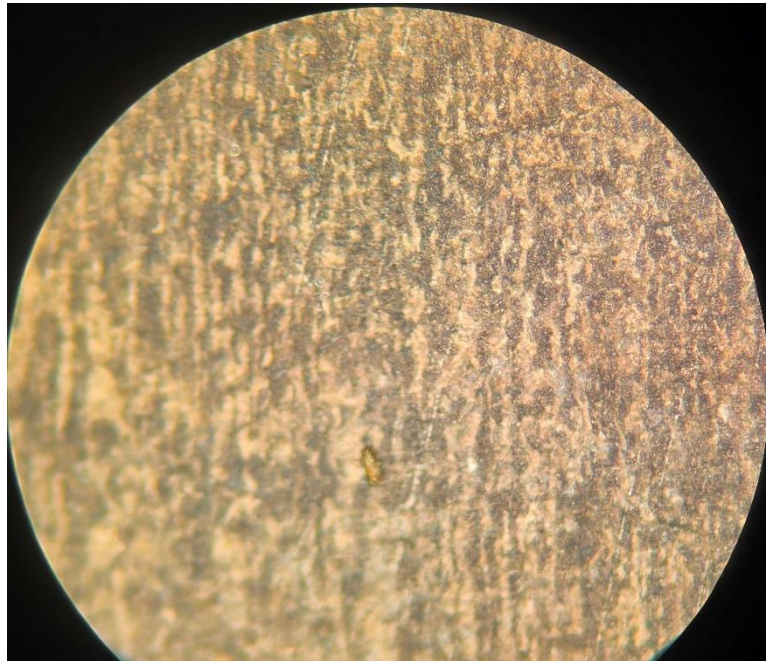
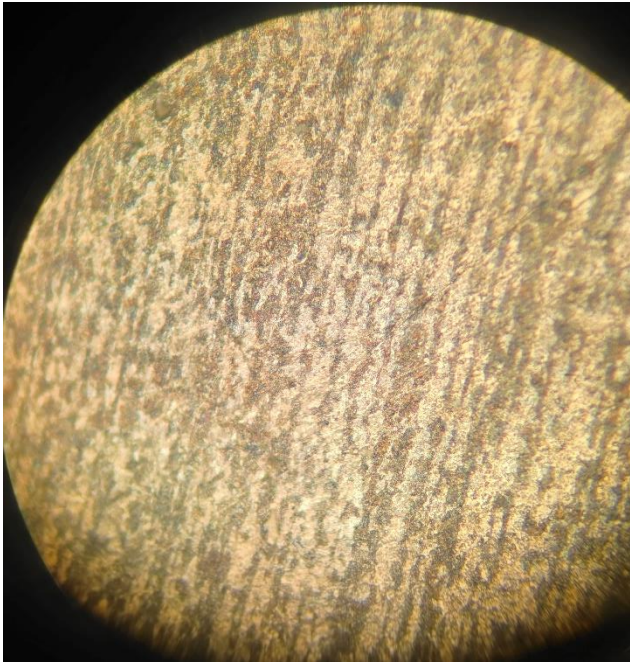


Figure 45-Surface structure of 1.6 μm Ra specimen (no coolant).

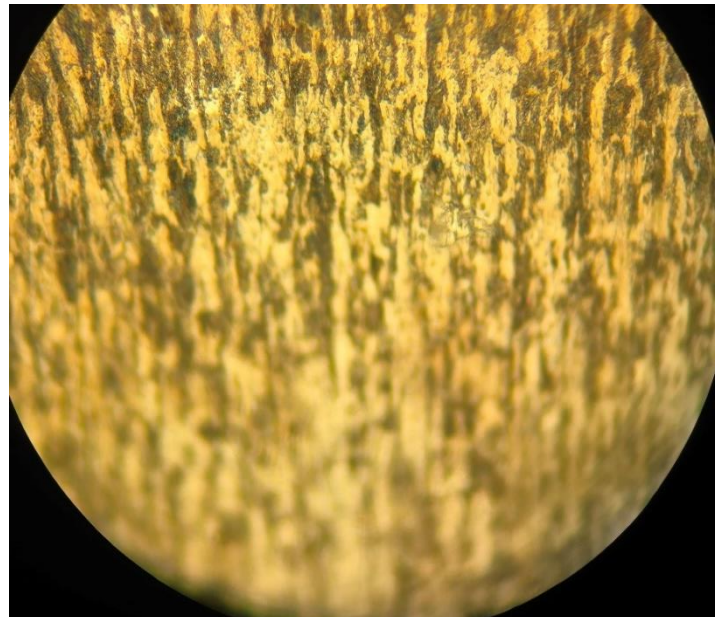
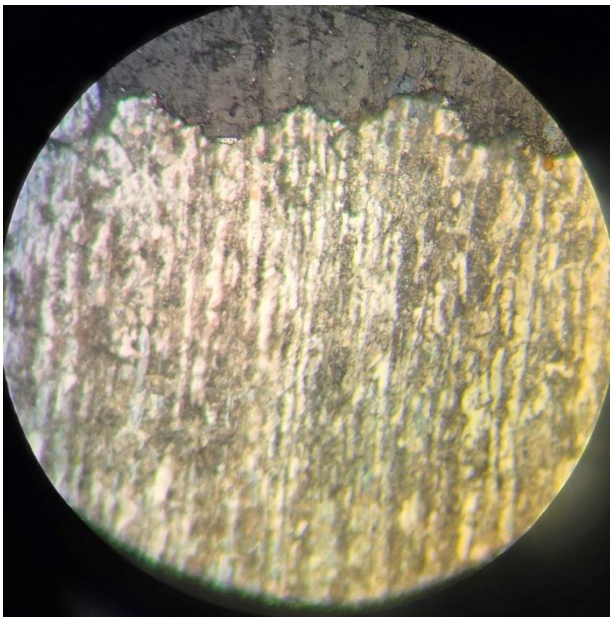


Figure 46-Surface structure of 3.2 μm specimen with surface defect.

All samples observed showed a ferrite-pearlite microstructure, which is consistent with cold-drawn EN8 steel (Callister and Rethwisch, 2020). As shown in Figs. 40 to 44, ferrite appears as the lighter grain, while the pearlite regions appear darker. This microstructure is typical of low- to medium-carbon steels (Feng et al., 2022) that have been slowly cooled after processing (D'Arcy et al., 2015). These phases' presence confirms the material's expected composition and thermal history. More notably, the grain morphology is small, elongated, and highly deformed, with a predominantly columnar alignment, which aligns with findings by Liu et al (2016). This is characteristic of cold drawing, a process in which the steel is pulled through a die at room temperature, introducing significant plastic deformation without allowing the material to recrystallise (Wei et al., 2020). The elongated grain structure indicates directional strain, supporting the conclusion that the material has undergone cold drawing. If the steel had been subjected to a temperature above the recrystallisation point, typically around 700°C for steel (ASM, 2007) the microstructure would display more equiaxed, rounded grains due to grain nucleation and growth during recrystallisation (Callister and Rethwisch, 2020). The absence of such features strongly suggests that the material experienced only cold working without subsequent annealing or heat treatment (Biswas et al., 2018).

The analysis was limited by the capabilities of the optical microscope available, which offered a maximum magnification of only 60x. This restricted the ability to resolve finer microstructural details. Furthermore, the dedicated digital camera system commonly used for capturing micrographs was unavailable, necessitating the use of a conventional digital camera positioned over the eyepiece. While this improvised method allowed for basic photographic documentation, it introduced further resolution loss and potential alignment errors, which may have affected the clarity and precision of the captured images.

7. Conclusions

This study clarified how three practical manufacturing variables—surface finish, the presence or absence of coolant during turning, and an intentionally machined surface defect—affect the tensile performance of EN8 medium-carbon steel. Tensile-test data for five specimen groups (6.4 μ m Ra (coolant), 3.2 μ m Ra (coolant), 1.6 μ m Ra (coolant), 1.6 μ m Ra (dry), and 3.2 μ m Ra (defect and coolant) were interpreted alongside optical-microscopy observations. The main findings and their implications are synthesised below.

7.1 Comparison of all specimen groups

7.1.1 Ultimate tensile strength (UTS).

UTS rose as the surface became smoother, improving by $\approx 4\%$ when roughness fell from 6.4 Ra (799 MPa) to 3.2 Ra (833 MPa), although it could be argued that it needs further investigation due to instrumental error. A further reduction to 1.6 Ra delivered no additional gain; the coolant-turned batch levelled off at 809 MPa while the dry-turned batch reached 822 MPa. The intentionally defective samples suffered the most significant drop, to 737 MPa around 10-15% below the other samples, confirming the potency of surface defects as crack initiators.

7.1.2 Yield strength (Rp0.2).

Surface quality exerted a more substantial influence on yield than on UTS. The 3.2 Ra specimens recorded the highest and most repeatable yield (735 MPa, $\pm 2\%$), some 15 % above the 6.4 Ra batch. The coolant-cut 1.6 Ra series exhibited erratic yields (478–748 MPa) owing to extensometer/grip compliance (Womack, 2024), whereas the dry-cut 1.6 Ra group stabilised at 611 MPa. Defect specimens (623 MPa) matched the dry 1.6 Ra average, but their proximity to UTS foreshadowed brittle fracture.

7.1.3 Failure mode

Undamaged specimens shed 20–25 % of their peak stress through stable necking before rupture, reflecting healthy ductility (Callister and Rethwisch, 2020). Defect specimens, by contrast, fractured only 5 % below UTS, exhibiting premature instability symptomatic of a brittle failure (Zhang, 1999).

7.1.4 Elastic modulus.

All batches yielded unrealistically low moduli (7–72 GPa). Because the calculated $R_{p0.2}$ depends on this slope (ASTM, 2013), the scatter in yield data broadly reveals instrumentation error rather than true material variability.

7.1.5 Manufacturing implications.

Moving from rough turning (6.4 Ra) to finish turning (3.2 Ra) produces the greatest economically justifiable strength benefit. Further refinement to 1.6 Ra offers diminishing returns. Coolant does not perceptibly enhance UTS but may introduce local thermal gradients that broaden yield scatter. Surface defects impose a decisive penalty on load-bearing capacity and should be stringently avoided or removed.

7.2 Comparison of 1.6 Ra with coolant vs. 1.6 Ra dry machined

The tensile-test data show no meaningful difference between the 1.6 Ra specimens machined with coolant and those cut dry. Averaged over three specimens each, the diameters (5.01 mm with coolant and 4.99 mm dry) and the calculated cross-sectional areas (19.70 mm² vs 19.54 mm²) differ by less than 1%, well inside the standard machining tolerance.

The maximum force at fracture is identical when rounded (16.06 kN for both groups), and the UTS, is virtually the same: 809 MPa for the coolant group versus 822 MPa for the dry group, a difference of about 1.5 %. Yield behaviour tells a similar story once scatter is considered. Although the coolant-cut set shows a higher average 0.2 % proof force (11.38 kN versus 11.94 kN dry) and the corresponding yield strength is lower (574 MPa versus 611 MPa), the coolant data are dominated by one specimen with an unusually high value (748 MPa), indicating a testing error rather than a machining effect.

Break load and stress also align closely (12.7 kN and 645 MPa for the coolant specimens compared with 12.2 kN and 626 MPa for the dry). Elastic modulus shows the most significant numerical discrepancy—37 GPa for the coolant group against 31 GPa dry—but here the coolant average is inflated by a single 72 GPa reading that almost certainly stems from an error with the extensometer attachment. Dry turning, while harsher on tools

(Zheng Yang et al., 2023), produced cleaner and highly reproducible stress–strain curves, although it may be argued that these results must be viewed with caution due to the clear elastic modulus errors.

7.3 Microscopy conclusions

Optical micrographs at 60 × magnification revealed no discernible difference in phase distribution or grain morphology between the five batches. Every specimen displayed the classic ferrite–pearlite lamellar matrix expected of cold-drawn EN8:

Ferrite (light) and pearlite (dark) grains were elongated and columnar, indicating substantial plastic deformation without recrystallisation (Feng et al., 2022).

Grain width remained uniformly fine, suggesting all specimens were manufactured from material with an identical chemical composition.

Neither the improved surface finish nor coolant use modified the material microstructure, confirming that the mechanical variations recorded originate from surface-integrity effects (surface finish, introduced surface defects) rather than changes in the material's microstructure. The analysis was constrained by the capabilities of the available optical microscope, which offered limited magnification. It could be argued that this limitation restricted the ability to resolve finer microstructural details. Moreover, the specialised digital camera system usually employed for taking micrographs was not accessible, requiring the use of a conventional digital camera aimed at the eyepiece. Although this alternative method enabled basic photographic documentation, it resulted in additional resolution loss and alignment issues, which may have negatively affected the clarity and accuracy of the images captured.

7.4 Summary of findings against the research objectives

Objective	Research outcomes
Assess the effects of various surface finishes on the tensile response of EN8 steel.	Smoother surfaces (down to 3.2 $\mu\text{m Ra}$) improved UTS and yield by up to 4 % and 15 %, respectively. Gains plateaued below 3.2 Ra, suggesting a practical optimum. These findings need further investigation as the gains are marginal and may be due to instrument error.
Assess the effect of coolant application on the tensile properties of EN8 1.6 Ra test specimens.	For EN8 specimens finished to 1.6 $\mu\text{m Ra}$, applying coolant neither drastically improves nor degrades tensile properties; testing errors overshadow any apparent deviations. Dry cutting samples yielded marginally more consistent mechanical data, but tool-life considerations, not material strength, should drive the coolant decision in this case.
Quantify the influence of surface defects on the tensile properties of EN8 steel.	A single circumferential defect reduced UTS by around 10-15 % and eliminated post-yield ductility, underscoring the criticality of surface integrity on EN8 steel components to reduce the risk of premature material failure.
Explore the microstructure of the EN8 test specimens.	Optical examination showed no observable differences at 60x magnification between all sample sets. Each sample exhibited deformed ferrite–pearlite microstructures consistent with cold-drawn EN8 steel, suggesting the machining of the test pieces has not significantly affected the material's microstructure.

8. Recommendations for further work

8.1 Tensile testing recommendations for further work

While this study has provided valuable insights into the tensile properties of EN8 steel under tensile loading, several avenues for further investigation remain. The primary recommendation concerns the unreliability of the Young's modulus values obtained throughout the tensile experiment (as shown in Chapters 5 and 6). Future research could repeat the experiment using a more suitable extensometer that fits a 25mm gauge length, thus eliminating the need for the extensometer testing attachment (Fig.15). Another enhancement might include increasing the preload on the samples to minimise slippage (as observed in Figs.25,27,29,31and33) caused by slack in the UTM grips (Womack, 2024). A further suggestion is to expand the sample size of the experiment from three to five specimens (Sunder Singh et al., 2020). This would increase the data available, thus offering a better statistical range to assess (ASTM, 2013). These suggestions would aim to yield more accurate results while examining whether the findings presented between sections 6.1.1 and 6.1.5 correlate or are proven to be incorrect. Further to this, section 6.1.6 shows that the manufacturer's Tensile Test results showed some variation against the results gained in this experiment; therefore, future work should address whether this is accurate without the overshadowing of instrumental error.

8.2 Microscopy recommendations for further work

Regarding the microscopy examination of the samples, future work should prioritise accessing higher-resolution microscopy to overcome the limitations encountered in this study. Optical microscopes equipped with magnifications of at least 100x are recommended (ASTM, 2010) which would reveal fine pearlitic lamellae that remained unresolved at 60x (Callister and Rethwisch, 2020). A study by Moleejane et al (2014) suggests performing a microscopy examination using a scanning electron microscope (SEM) to complement the optical study. They found that using an SEM captured more detail at a higher resolution, making it more suitable for identifying minor microstructural defects, although optical microscopy is better for grain measurements and offers a broader field of view. In tandem with a C-mount digital camera with live-view software, these suggestions would improve image clarity by eliminating the parallax and alignment errors inherent in the improvised hand-held setup used here.

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10. Appendices

10.1 Appendix 1-8mm EN8 mill test certificate

This appendix shows the mill test certificate for the material used for future experimental replication.

[illegible]

10.2 Appendix 2- ISO 6892-1

This appendix shows the relevant pages from ISO 6892-1 for reference purposes of this study.



National foreword

This British Standard is the UK implementation of EN ISO 6892-1:2019. It is identical to ISO 6892-1:2019. It supersedes BS EN ISO 6892-1:2016, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee ISE/101/1, Uniaxial and Ductility Testing.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2020

ISBN 978 0 539 04735 6

ICS 77.040.10

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 January 2020.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

BS EN ISO 6892-1:2019

EUROPEAN STANDARD **EN ISO 6892-1**

NORME EUROPÉENNE

EUROPÄISCHE NORM December 2019

ICS 77.040.10 Supersedes EN ISO 6892-1:2016

English Version

Metallic materials - Tensile testing - Part 1: Method of test at room temperature (ISO 6892-1:2019)

Matériaux métalliques - Essai de traction - Partie 1:
Méthode d'essai à température ambiante (ISO 6892-
1:2019)

Metallische Werkstoffe - Zugversuch - Teil 1:
Prüfverfahren bei Raumtemperatur (ISO 6892-1:2019)

This European Standard was approved by CEN on 12 November 2019.

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Ref. No. EN ISO 6892-1:2019 E

European foreword

This document (EN ISO 6892-1:2019) has been prepared by Technical Committee ISO/TC 164 "Mechanical testing of metals" in collaboration with Technical Committee CEN/TC 459/SC 1 "Test methods for steel (other than chemical analysis)" the secretariat of which is held by AFNOR.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2020, and conflicting national standards shall be withdrawn at the latest by June 2020.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document supersedes EN ISO 6892-1:2016.

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Endorsement notice

The text of ISO 6892-1:2019 has been approved by CEN as EN ISO 6892-1:2019 without any modification.

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 1, *Uniaxial testing*.

This third edition cancels and replaces the second edition (ISO 6892-1:2016), of which it constitutes a minor revision. The changes compared to the previous edition are as follows:

- correction of the title of a standard in [Clause 2](#);
- correction of the designation "coefficient of determination" ("coefficient of determination" instead of "coefficient of correlation");
- correction of [Formula \(1\)](#);
- wording in [10.3.2.1](#);
- wording in the key of [Figure 9](#);
- wording in [Table B.2](#);
- wording in [Table D.3](#);
- correction of the references.

A list of all parts in the ISO 6892 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

During discussions concerning the speed of testing in the preparation of ISO 6892, it was decided to recommend the use of strain rate control in future revisions.

In this document, there are two methods of testing speeds available. The first, method A, is based on strain rates (including crosshead separation rate) and the second, method B, is based on stress rates. Method A is intended to minimize the variation of the test rates during the moment when strain rate sensitive parameters are determined and to minimize the measurement uncertainty of the test results. Therefore, and out of the fact that often the strain rate sensitivity of the materials is not known, the use of method A is strongly recommended.

NOTE In what follows, the designations "force" and "stress" or "extension", "percentage extension", and "strain", respectively, are used on various occasions (as figure axis labels or in explanations for the determination of different properties). However, for a general description or point on a curve, the designations "force" and "stress" or "extension", "percentage extension", and "strain", respectively, can be interchanged.

Metallic materials — Tensile testing —

Part 1: Method of test at room temperature

1 Scope

This document specifies the method for tensile testing of metallic materials and defines the mechanical properties which can be determined at room temperature.

NOTE [Annex A](#) contains further recommendations for computer controlled testing machines.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*

ISO 9513, *Metallic materials — Calibration of extensometer systems used in uniaxial testing*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1 gauge length

L
length of the parallel portion of the test piece on which elongation is measured at any moment during the test

3.1.1 original gauge length

L_0
length between *gauge length* (3.1) marks on the test piece measured at room temperature before the test

3.1.2 final gauge length after fracture

L_u
length between *gauge length* (3.1) marks on the test piece measured after rupture, at room temperature, the two pieces having been carefully fitted back together so that their axes lie in a straight line

3.2
parallel length

L_c
length of the parallel reduced section of the test piece

Note 1 to entry: The concept of parallel length is replaced by the concept of distance between grips for unmachined test pieces.

3.3
elongation

increase in the *original gauge length* (3.1.1) at any moment during the test

3.4
percentage elongation
elongation (3.3) expressed as a percentage of the *original gauge length* (3.1.1)

3.4.1
percentage permanent elongation
increase in the *original gauge length* (3.1.1) of a test piece after removal of a specified stress, expressed as a percentage of the *original gauge length* (3.1.1)

3.4.2
percentage elongation after fracture
 A
permanent *elongation* (3.3) of the gauge length after fracture ($L_u - L_0$), expressed as a percentage of the *original gauge length* (3.1.1)

Note 1 to entry: For further information, see 8.1.

3.5
extensometer gauge length

L_e
initial gauge length of the extensometer used for measurement of *extension* (3.6)

Note 1 to entry: For the determination of several properties which are based (partly or complete) on extension, e.g. R_p , A_0 or A_g , the use of an extensometer is mandatory.

Note 2 to entry: For further information, see 8.3.

3.6
extension
increase in the *extensometer gauge length* (3.5), at any moment during the test

3.6.1
percentage extension
strain
 ϵ
extension (3.6) expressed as a percentage of the *extensometer gauge length* (3.5)

Note 1 to entry: ϵ is commonly called engineering strain.

3.6.2
percentage permanent extension
increase in the *extensometer gauge length* (3.5), after removal of a specified stress (3.10) from the test piece, expressed as a percentage of the extensometer gauge length

**3.6.3
percentage yield point extension**

A_p
<discontinuous yielding materials> extension (3.6) between the start of yielding and the start of uniform work-hardening, expressed as a percentage of the extensometer gauge length (3.5)

Note 1 to entry: See Figure 2.

**3.6.4
percentage total extension at maximum force**

A_{gt}
total extension (3.6) (elastic extension plus plastic extension) at maximum force, expressed as a percentage of the extensometer gauge length (3.5)

Note 1 to entry: See Figure 1.

**3.6.5
percentage plastic extension at maximum force**

A_p
plastic extension (3.6) at maximum force, expressed as a percentage of the extensometer gauge length (3.5)

Note 1 to entry: See Figure 1.

**3.6.6
percentage total extension at fracture**

A_t
total extension (3.6) (elastic extension plus plastic extension) at the moment of fracture, expressed as a percentage of the extensometer gauge length (3.5)

Note 1 to entry: See Figure 1.

**3.7
testing rate**
rate (resp. rates) used during the test

**3.7.1
strain rate**

$\dot{\epsilon}_{\epsilon_0}$
increase of strain, measured with an extensometer, in extensometer gauge length (3.5), per time

**3.7.2
estimated strain rate over the parallel length**

$\dot{\epsilon}_{\epsilon_0}$
value of the increase of strain over the parallel length (3.2) of the test piece per time based on the crosshead separation rate (3.7.3) and the parallel length of the test piece

**3.7.3
crosshead separation rate**

v_c
displacement of the crossheads per time

**3.7.4
stress rate**

$\dot{R}$
increase of stress (3.10) per time

Note 1 to entry: Stress rate is only used in the elastic part of the test (method B) (see also 10.3.3).

3.8 percentage reduction of area

Z
maximum change in cross-sectional area which has occurred during the test ($S_0 - S_u$), expressed as a percentage of the original cross-sectional area, S_0 :

$$Z = \frac{S_0 - S_u}{S_0} \cdot 100$$

3.9 Maximum force

3.9.1 maximum force

F_m
<materials displaying no discontinuous yielding> highest force that the test piece withstands during the test

3.9.2 maximum force

F_m
<materials displaying discontinuous yielding> highest force that the test piece withstands during the test after the beginning of work-hardening

Note 1 to entry: For materials which display discontinuous yielding, but where no work-hardening can be established, F_m is not defined in this document [see footnote to [Figure 8 c\)](#)].

Note 2 to entry: See [Figure 8 a\)](#) and b).

3.10 stress

R
at any moment during the test, force divided by the original cross-sectional area, S_0 , of the test piece

Note 1 to entry: All references to stress in this document are to engineering stress.

3.10.1 tensile strength

R_m
stress ([3.10](#)) corresponding to the *maximum force* ([3.9.2](#))

3.10.2 yield strength

when the metallic material exhibits a yield phenomenon, stress ([3.10](#)) corresponding to the point reached during the test at which plastic deformation occurs without any increase in the force

3.10.2.1 upper yield strength

R_{eH}
maximum value of stress ([3.10](#)) prior to the first decrease in force

Note 1 to entry: See [Figure 2](#).

3.10.2.2 lower yield strength

R_{eL}
lowest value of stress ([3.10](#)) during plastic yielding, ignoring any initial transient effects

Note 1 to entry: See [Figure 2](#).

3.10.3 proof strength, plastic extension

R_p
stress (3.10) at which the plastic extension (3.6) is equal to a specified percentage of the *extensometer gauge length* (3.5)

Note 1 to entry: Adapted from ISO/TR 25679:2005, "proof strength, non-proportional extension".

Note 2 to entry: A suffix is added to the subscript to indicate the prescribed percentage, e.g. $R_{p0,2}$.

Note 3 to entry: See Figure 3.

3.10.4 proof strength, total extension

R_t
stress (3.10) at which total extension (3.6) (elastic extension plus plastic extension) is equal to a specified percentage of the *extensometer gauge length* (3.5)

Note 1 to entry: A suffix is added to the subscript to indicate the prescribed percentage, e.g. $R_{t0,5}$.

Note 2 to entry: See Figure 4.

3.10.5 permanent set strength

R_p
stress (3.10) at which, after removal of force, a specified permanent elongation (3.3) or extension (3.6), expressed respectively as a percentage of *original gauge length* (3.1.1), or *extensometer gauge length* (3.5), has not been exceeded

Note 1 to entry: A suffix is added to the subscript to indicate the specified percentage of the original gauge length, L_0 , or of the extensometer gauge length, L_e , e.g. $R_{p0,2}$.

Note 2 to entry: See Figure 5.

3.11 fracture

phenomenon which is deemed to occur when total separation of the test piece occurs

Note 1 to entry: Criteria for fracture for computer controlled tests are given in Figure A.2.

3.12 computer-controlled tensile testing machine

machine for which the control and monitoring of the test, the measurements, and the data processing are undertaken by computer

3.13 modulus of elasticity

E
quotient of change of stress ΔR and change of percentage extension Δe in the range of evaluation, multiplied by 100 %

$$E = \frac{\Delta R}{\Delta e} \cdot 100 \%$$

Note 1 to entry: It is recommended to report the value in GPa rounded to the nearest 0,1 GPa and according to ISO 80000-1.

3.14 default value

lower or upper value for stress (3.10), respectively strain (3.6.1), which is used for the description of the range where the *modulus of elasticity* (3.13) is calculated

3.15 coefficient of determination

R^2
additional result of the linear regression which describes the quality of the stress-strain curve in the evaluation range

Note 1 to entry: The used symbol R^2 is a mathematical representation of regression and is no expression for a squared stress value.

3.16 standard deviation of the slope

S_m
additional result of the linear regression which describes the difference of the stress (3.10) values from the best fit line for the given extension (3.6.1) values in the evaluation range

3.17 relative standard deviation of the slope

$S_{m(\text{rel})}$
quotient of the standard deviation of the slope (3.16) and the slope in the evaluation range, multiplied by 100 %

$$S_{m(\text{rel})} = \frac{S_m}{E} 100 \%$$

4 Symbols

The symbols used in this document and corresponding designations are given in Table 1.

Table 1 — Symbols and designations

Symbol	Unit	Designation
Test piece		
a_{pr}^{a}	mm	original thickness of a flat test piece or wall thickness of a tube
b_0	mm	original width of the parallel length of a flat test piece or average width of the longitudinal strip taken from a tube or width of flat wire
d_0	mm	original diameter of the parallel length of a circular test piece, or diameter of round wire or internal diameter of a tube
D_0	mm	original external diameter of a tube
L_0	mm	original gauge length
L'_0	mm	initial gauge length for determination of A_{w}^{c} (see Annex I)
L_{e}	mm	parallel length
L_{e}	mm	extensometer gauge length
L_{t}	mm	total length of test piece
L_{u}	mm	final gauge length after fracture
L'_{u}	mm	final gauge length after fracture for determination of A_{w}^{c} (see Annex I)
^a Symbol used in steel tube product standards.		
^b 1 MPa = 1 N mm ⁻² .		
^c The calculation of the modulus of elasticity is described in Annex G. It is not required to use Annex G to determine the slope of the elastic part of the stress-percentage extension curve for the determination of proof strength.		
^d In the elastic part of the stress-percentage extension curve, the value of the slope may not necessarily represent the modulus of elasticity. This value may closely agree with the value of the modulus of elasticity if optimal conditions are used (see Annex G).		
CAUTION — The factor 100 is necessary if percentage values are used.		

Table 1 (continued)

Symbol	Unit	Designation
S_o	mm ²	original cross-sectional area of the parallel length
S_a	mm ²	minimum cross-sectional area after fracture
k	—	coefficient of proportionality (see 6.4.1)
Z	%	percentage reduction of area
Elongation		
A	%	percentage elongation after fracture (see 3.4.2)
$A_{0.2}$	%	percentage plastic elongation without necking (see Annex I)
Extension		
e	%	extension
A_e	%	percentage yield point extension
A_p	%	percentage plastic extension at maximum force, F_m
A_{Tm}	%	percentage total extension at maximum force, F_m
A_f	%	percentage total extension at fracture
ΔL_m	mm	extension at maximum force
ΔL_f	mm	extension at fracture
Rates		
$\dot{\epsilon}_{Lp}$	s ⁻¹	strain rate
$\dot{\epsilon}_{Lc}$	s ⁻¹	estimated strain rate over the parallel length
$\dot{R}$	MPa s ⁻¹	stress rate
v_c	mm s ⁻¹	crosshead separation rate
Force		
F_m	N	maximum force
Yield strength — Proof strength — Tensile strength		
R	MPa ^b	stress
R_{eH}	MPa	upper yield strength
R_{eL}	MPa	lower yield strength
R_m	MPa	tensile strength
R_p	MPa	proof strength, plastic extension
R_r	MPa	specified permanent set strength
R_t	MPa	proof strength, total extension
Modulus of elasticity — slope of the stress-percentage extension curve		
E	GPa	modulus of elasticity ^c
m	MPa	slope of the stress-percentage extension curve at a given moment of the test
m_e	MPa	slope of the elastic part of the stress-percentage extension curve ^d
R_1	MPa	lower stress value
R_2	MPa	upper stress value

^a Symbol used in steel tube product standards.

^b 1 MPa = 1 N mm⁻².

^c The calculation of the modulus of elasticity is described in Annex G. It is not required to use Annex G to determine the slope of the elastic part of the stress-percentage extension curve for the determination of proof strength.

^d In the elastic part of the stress-percentage extension curve, the value of the slope may not necessarily represent the modulus of elasticity. This value may closely agree with the value of the modulus of elasticity if optimal conditions are used (see Annex G).

CAUTION — The factor 100 is necessary if percentage values are used.

Table 1 (continued)

Symbol	Unit	Designation
e_1	%	lower strain value
e_2	%	upper strain value
R^2	—	coefficient of determination
S_m	MPa	standard deviation of the slope
$S_{m(rel)}$	%	relative standard deviation of the slope
^a Symbol used in steel tube product standards.		
^b 1 MPa = 1 N mm ⁻² .		
^c The calculation of the modulus of elasticity is described in Annex G. It is not required to use Annex G to determine the slope of the elastic part of the stress-percentage extension curve for the determination of proof strength.		
^d In the elastic part of the stress-percentage extension curve, the value of the slope may not necessarily represent the modulus of elasticity. This value may closely agree with the value of the modulus of elasticity if optimal conditions are used (see Annex G).		
CAUTION — The factor 100 is necessary if percentage values are used.		

5 Principle

The test involves straining a test piece by tensile force, generally to fracture, for the determination of one or more of the mechanical properties defined in Clause 3.

The test shall be carried out at room temperature between 10 °C and 35 °C, unless otherwise specified. For laboratory environments outside the stated requirement, it is the responsibility of the testing laboratory to assess the impact on testing and/or calibration data produced with and for testing machines operated in such environments. When testing and calibration activities are performed outside the temperature limits of 10 °C and 35 °C, the temperature shall be recorded and reported. If significant temperature gradients are present during testing and/or calibration, measurement uncertainty may increase and out of tolerance conditions may occur.

Tests carried out under controlled conditions shall be made at a temperature of 23 °C ± 5 °C.

If the determination of the modulus of elasticity is requested in the tensile test, this shall be done in accordance with Annex G.

6 Test pieces

6.1 Shape and dimensions

6.1.1 General

The shape and dimensions of the test pieces may be constrained by the shape and dimensions of the metallic product from which the test pieces are taken.

The test piece is usually obtained by machining a sample from the product or a pressed blank or casting. However, products of uniform cross-section (sections, bars, wires, etc.) and also as-cast test pieces (i.e. for cast iron and non-ferrous alloys) may be tested without being machined.

The cross-section of the test pieces may be circular, square, rectangular, annular or, in special cases, some other uniform cross-section.

Preferred test pieces have a direct relationship between the original gauge length, L_0 , and the original cross-sectional area, S_0 , expressed by the formula $L_0 = k \sqrt{S_0}$, where k is a coefficient of proportionality, and are called proportional test pieces. The internationally adopted value for k is 5,65. The original gauge length shall be not less than 15 mm. When the cross-sectional area of the test piece is too small

for this requirement to be met with $k = 5,65$, a higher value (preferably 11,3) or a non-proportional test piece may be used.

NOTE By using an original gauge length smaller than 20 mm, the uncertainty of the result "elongation after fracture" will be increased.

For non-proportional test pieces, the original gauge length, L_0 , is independent of the original cross-sectional area, S_0 .

The dimensional tolerances of the test pieces shall be in accordance with Annexes B to E (see 6.2).

Other test pieces such as those specified in relevant product standards or national standards may be used by agreement with the customer, e.g. ISO 3183^[4] (API 5L), ISO 11960^[4] (API 5CT), ASTM A370^[4], ASTM E8M^[4], DIN 50125^[4], IACS W2^[4], and JIS Z 2241^[4].

6.1.2 Machined test pieces

Machined test pieces shall incorporate a transition radius between the gripped ends and the parallel length if these have different dimensions. The dimensions of the transition radius are important and it is recommended that they be defined in the material specification if they are not given in the appropriate annex (see 6.2).

The gripped ends may be of any shape to suit the grips of the testing machine. The axis of the test piece shall coincide with the axis of application of the force.

The parallel length, L_0 , or, in the case where the test piece has no transition radii, the free length between the grips, shall always be greater than the original gauge length, L_0 .

6.1.3 Unmachined test pieces

If the test piece consists of an unmachined length of the product or of an unmachined test bar, the free length between the grips shall be sufficient for gauge marks to be at a reasonable distance from the grips (see Annexes B to E).

As-cast test pieces shall incorporate a transition radius between the gripped ends and the parallel length. The dimensions of this transition radius are important and it is recommended that they be defined in the product standard. The gripped ends may be of any shape to suit the grips of the testing machine provided that they enable the centre of the test piece to coincide with the axis of application of force. The parallel length, L_0 , shall always be greater than the original gauge length, L_0 .

6.2 Types

The main types of test pieces are defined in Annexes B to E according to the shape and type of product, as shown in Table 2. Other types of test pieces can be specified in product standards.

Table 2 — Main types of test pieces according to product type

Dimensions in millimetres

Type of product		Corresponding annex
Sheets — Plates — Flats	Wire — Bars — Sections	
	  	
Thickness a	Diameter or side	
$0,1 \leq a < 3$	—	B
—	< 4	C
$a \geq 3$	≥ 4	D
Tubes		E

6.3 Preparation of test pieces

The test pieces shall be taken and prepared in accordance with the requirements of the relevant International Standards for the different materials (e.g. ISO 377).

7 Determination of original cross-sectional area

The relevant dimensions of the test piece should be measured at sufficient cross-sections perpendicular to the longitudinal axis in the central region of the parallel length of the test piece.

A minimum of three cross-sections is recommended.

The original cross-sectional area, S_0 , is the average cross-sectional area and shall be calculated from the measurements of the appropriate dimensions.

The accuracy of this calculation depends on the nature and type of the test piece. Annexes B to E describe methods for the evaluation of S_0 for different types of test pieces and contain specifications for the accuracy of measurement.

All measuring devices used for the determination of the original cross-sectional area shall be calibrated to the appropriate reference standards with traceability to a national measurement system.

8 Original gauge length and extensometer gauge length

8.1 Choice of the original gauge length

For proportional test pieces, if the original gauge length is not equivalent to $5,65\sqrt{S_0}$, where S_0 is the original cross-sectional area of the parallel length, the symbol A should be supplemented by a subscript indicating the coefficient of proportionality used, e.g. $A_{11,3}$ indicates a percentage elongation of the gauge length, L_0 , according to [Formula \(1\)](#):

$$L_0 = 11,3\sqrt{S_0} \quad (1)$$

NOTE $5,65\sqrt{S_0} = 5\sqrt{4S_0/\pi}$.

For non-proportional test pieces (see [Annex B](#) and [Annex D](#)), the symbol A should be supplemented by a subscript indicating the original gauge length used, expressed in millimetres, e.g. $A_{80\text{ mm}}$ indicates a percentage elongation of a gauge length, L_0 , of 80 mm.

8.2 Marking the original gauge length

For the manual determination of the elongation after fracture A , each end of the original gauge length, L_g , shall be marked by means of fine marks, scribed lines, or punch marks, but not by marks which could result in premature fracture. The original gauge length shall be marked to an accuracy of $\pm 1\%$.

For proportional test pieces, the calculated value of the original gauge length may be rounded to the nearest multiple of 5 mm, provided that the difference between the calculated and marked gauge length is less than 10 % of L_g .

If the parallel length, L_p , is much greater than the original gauge length, as, for instance, with unmachined test pieces, a series of overlapping gauge lengths may be marked.

In some cases, it can be helpful to draw a line parallel to the longitudinal axis, along which the gauge lengths are marked.

8.3 Choice of the extensometer gauge length

For measurement of yield and proof strength parameters, L_e should span as much of the parallel length of the test piece as possible. Ideally, as a minimum, L_e should be greater than $0.50L_p$, but less than approximately $0.9L_p$. This should ensure that the extensometer detects all yielding events that occur in the test piece. Further, for measurement of parameters "at" or "after reaching" maximum force, L_e should be approximately equal to L_g .

9 Accuracy of testing apparatus

The force-measuring system of the testing machine shall be in accordance with ISO 7500-1, class 1, or better.

For the determination of proof strength (plastic or total extension), the extensometer used shall be in accordance with ISO 9513, class 1 or better, in the relevant range. For other properties (with extensions greater than 5 %), an ISO 9513, class 2 extensometer in the relevant range may be used.

10 Conditions of testing

10.1 Setting the force zero point

The force-measuring system shall be set to zero after the testing loading train has been assembled, but before the test piece is actually gripped at both ends. Once the force zero point has been set, the force-measuring system shall not be changed in any way during the test.

NOTE The use of this method ensures that, on one hand, the weight of the gripping system is compensated for in the force measurement, and on the other hand, any force resulting from the clamping operation does not affect this measurement.

10.2 Method of gripping

The test pieces shall be gripped by suitable means, such as wedges, screwed grips, parallel jaw faces, or shouldered holders.

Every endeavour should be made to ensure that test pieces are held in such a way that the force is applied as axially as possible, in order to minimize bending (more information is given in ASTM E1012^[6], for example). This is of particular importance when testing brittle materials or when determining proof strength (plastic extension), proof strength (total extension), or yield strength.

In order to ensure the alignment of the test piece and grip arrangement, a preliminary force may be applied provided it does not exceed a value corresponding to 5 % of the specified or expected yield

strength. A correction of the extension should be carried out to take into account the effect of the preliminary force.

10.3 Testing rates

10.3.1 General information regarding testing rates

Unless otherwise agreed, the choice of method (A1, A2, or B) and test rates are at the discretion of the producer or the test laboratory assigned by the producer, provided that these meet the requirements of this document.

NOTE 1 The difference between Method A and Method B is that the necessary testing speed of Method A is defined at the point of interest (e.g. $R_{p0.2}$), where the property has to be determined, whereas, in Method B, the necessary testing speed is set in the elastic range before the property (e.g. $R_{p0.2}$) has to be determined.

Under certain conditions using Method B (e.g. for some steels a stress rate in the elastic range of approximately 30 MPa/s, using a testing rig and clamping system with high stiffness and a test piece geometry according to Annex B, Table B.1, Test piece type 2), a strain rate near the range 2 of Method A may be observed.

NOTE 2 Product standards and corresponding test standards (e.g. aerospace standards) can specify test rates that are different from those contained in this document.

10.3.2 Testing rate based on strain rate (method A)

10.3.2.1 General

Method A is intended to minimize the variation of the test rates during the moment when strain rate sensitive parameters are determined and to minimize the measurement uncertainty of the test results.

Two different types of strain rate control are described in this subclause.

- Method A1 closed loop involves the control of the strain rate itself, $\dot{\epsilon}_{L_p}$, that is based on the feedback obtained from an extensometer.
- Method A2 open loop involves the control of the estimated strain rate over the parallel length, $\dot{\epsilon}_{L_e}$, which is achieved by using the crosshead separation rate calculated by multiplying the required strain rate by the parallel length [see Formula (2)].

NOTE A more rigorous strain rate estimation procedure for Method A2 is described in Annex F.

If a material shows no discontinuous yielding and the force remains nominally constant, the strain rate, $\dot{\epsilon}_{L_p}$, and the estimated strain rate over the parallel length, $\dot{\epsilon}_{L_e}$, are approximately equal. Differences exist if the material exhibits discontinuous or serrated yielding (e.g. some steels and AlMg alloys in the yield point extension range, or materials which show serrated yielding like the Portevin-Le Chatelier effect) or if necking occurs. If the force is increasing, the strain rate [if the crosshead separation rate is calculated using Formula (2)] may be below the target strain rate due to the compliance of the testing machine.

The testing rate shall conform to the following requirements.

- a) Unless otherwise specified, any convenient speed of testing may be used up to a stress equivalent to half of the expected yield strength. Above this range and for the determination of R_{eH} , R_p or R_t , the specified strain rate, $\dot{\epsilon}_{L_p}$ (or for Method A2 the crosshead separation rate v_c), shall be applied. In this range, to eliminate the influence of the compliance of the tensile testing machine, the use of an extensometer measuring the extension of the test piece is necessary to have accurate control over the strain rate. For testing machines unable to control by strain rate, method A2 may be used.

- b) During discontinuous yielding, the estimated strain rate over the parallel length, $\dot{\epsilon}_{L_c}$ (see 3.7.2), should be applied. In this range, it is impossible to control the strain rate using the extensometer clamped on to the test piece because local yielding can occur outside the extensometer gauge length. The required estimated strain rate over the parallel length may be maintained in this range sufficiently accurately using a constant crosshead separation rate, v_c (see 3.7.3) (open loop).

$$v_c = L_c \dot{\epsilon}_{L_c} \quad (2)$$

where

$\dot{\epsilon}_{L_c}$ is the estimated strain rate over the parallel length;

L_c is the parallel length.

- c) In the range following R_p or R_t or end of yielding (see 3.7.2), $\dot{\epsilon}_{L_e}$ or $\dot{\epsilon}_{L_c}$ can be used. The use of $\dot{\epsilon}_{L_c}$ is recommended to avoid any control problems which may arise if necking occurs outside the extensometer gauge length.

The strain rates specified in 10.3.2.2 to 10.3.2.4 shall be maintained during the determination of the relevant material property (see also Figure 9).

During switching to another strain rate or to another control mode, no discontinuities in the stress-strain curve should be introduced which distort the values of R_m , A_g or A_{gt} (see Figure 10). This effect can be reduced by a suitable gradual switch between the rates.

The shape of the stress-strain curve in the work-hardening range can also be influenced by the strain rate. The testing rate used should be documented (see 10.3.4).

10.3.2.2 Strain rate for the determination of the upper yield strength, R_{eH} , or proof strength properties, R_p and R_t

The strain rate, $\dot{\epsilon}_{L_e}$, shall be kept as constant as possible up to and including the determination of R_{eH} or R_p or R_t . During the determination of these material properties, the strain rate, $\dot{\epsilon}_{L_e}$, shall be in one of the two following specified ranges (see also Figure 9).

Range 1: $\dot{\epsilon}_{L_e} = 0,000\ 07\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$.

Range 2: $\dot{\epsilon}_{L_e} = 0,000\ 25\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$ (recommended, unless otherwise specified).

If the testing machine is not able to control the strain rate directly, Method A2 shall be used.

10.3.2.3 Strain rate for the determination of the lower yield strength, R_{eL} , and percentage yield point extension, A_g

Following the detection of the upper yield strength (see A.3.2), the estimated strain rate over the parallel length, $\dot{\epsilon}_{L_c}$, shall be maintained in one of the following two specified ranges (see Figure 9) until discontinuous yielding has ended.

Range 2: $\dot{\epsilon}_{L_c} = 0,000\ 25\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$ (recommended, when R_{eL} is determined).

Range 3: $\dot{\epsilon}_{L_c} = 0,002\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$.

10.3.2.4 Strain rate for the determination of the tensile strength, R_m , percentage elongation after fracture, A , percentage total extension at the maximum force, A_{gt} , percentage plastic extension at maximum force, A_g , and percentage reduction area, Z

After determination of the required yield/proof strength properties, the estimated strain rate over the parallel length, $\dot{\epsilon}_{L_e}$, shall be changed to one of the following specified ranges (see Figure 9).

Range 2: $\dot{\epsilon}_{L_e} = 0,000\ 25\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$.

Range 3: $\dot{\epsilon}_{L_e} = 0,002\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$.

Range 4: $\dot{\epsilon}_{L_e} = 0,006\ 7\ s^{-1}$, with a relative tolerance of $\pm 20\ \%$ ($0,4\ min^{-1}$, with a relative tolerance of $\pm 20\ \%$) (recommended, unless otherwise specified).

If the purpose of the tensile test is only to determine the tensile strength, then an estimated strain rate over the parallel length of the test piece according to range 3 or 4 may be applied throughout the entire test.

10.3.3 Testing rate based on stress rate (method B)

10.3.3.1 General

The testing rates shall conform to the following requirements depending on the nature of the material. Unless otherwise specified, any convenient speed of testing may be used up to a stress equivalent to half of the specified yield strength. The testing rates above this point are specified below.

NOTE It is not the intent of Method B to maintain constant stress rate or to control stress rate with closed loop force control while determining yield properties, but only to set the crosshead speed to achieve the target stress rate in the elastic region (see Table 4). When a specimen being tested begins to yield, the stressing rate decreases and can even become negative in the case of a specimen with discontinuous yielding. The attempt to maintain a constant stressing rate through the yielding process requires the testing machine to operate at extremely high speeds and, in most cases, this is neither practical nor desirable.

10.3.3.2 Yield and proof strengths

10.3.3.2.1 Upper yield strength, R_{eH}

The rate of separation of the crossheads of the machine shall be kept as constant as possible and within the limits corresponding to the stress rates in Table 3.

NOTE For information, typical materials having a modulus of elasticity smaller than 150 000 MPa include magnesium, aluminium alloys, brass, and titanium. Typical materials with a modulus of elasticity greater than 150 000 MPa include wrought iron, steel, tungsten, and nickel-based alloys.

Table 3 — Stress rate

Modulus of elasticity of the material E MPa	Stress rate R MPa s^{-1}	
	min.	max.
<150 000	2	20
$\geq 150\ 000$	6	60

10.3.3.2.2 Lower yield strength, R_{eL}

If only the lower yield strength is being determined, the strain rate during yield of the parallel length of the test piece shall be between $0,000\ 25\ s^{-1}$ and $0,002\ 5\ s^{-1}$. The strain rate within the parallel

length shall be kept as constant as possible. If this rate cannot be regulated directly, it shall be fixed by regulating the stress rate just before yield begins, the controls of the machine not being further adjusted until completion of yield.

In no case shall the stress rate in the elastic range exceed the maximum rates given in [Table 3](#).

10.3.3.2.3 Upper and lower yield strengths, R_{eH} and R_{eL}

If both upper and lower yield strengths are determined during the same test, the conditions for determining the lower yield strength shall be complied with (see [10.3.3.2.2](#)).

10.3.3.2.4 Proof strength (plastic extension) and proof strength (total extension), R_p and R_t

The crosshead separation rate of the machine shall be kept as constant as possible and within the limits corresponding to the stress rates in [Table 3](#) for the elastic range. This crosshead separation rate shall be maintained up to the proof strength (plastic extension or total extension). In any case, the strain rate shall not exceed $0,002\ 5\ s^{-1}$.

10.3.3.2.5 Rate of separation

If the testing machine is not capable of measuring or controlling the strain rate, a crosshead separation rate equivalent to the stress rate given in [Table 3](#) shall be used until completion of yield.

10.3.3.3 Tensile strength, R_m , percentage elongation after fracture, A , percentage total extension at the maximum force, A_g , percentage plastic extension at maximum force, A_p and percentage reduction area, Z

After determination of the required yield/proof strength properties, the test rate may be increased to a strain rate (or equivalent crosshead separation rate) no greater than $0,008\ s^{-1}$.

If only the tensile strength of the material is to be measured, a single strain rate can be used throughout the test which shall not exceed $0,008\ s^{-1}$.

10.3.4 Report of the chosen testing conditions

In order to report the test control mode and testing rates in an abridged form, the following system of abbreviation can be used:

ISO 6892-1 Annn, or ISO 6892-1 Bn

where "A" defines the use of method A (strain rate based), and "B" the use of method B (stress rate based). The symbols "nnn" are a series of up to 3 characters that refer to the rates used during each phase of the test, as defined in [Figure 9](#), and "n" may be added to indicate the stress rate (in $MPa\ s^{-1}$) selected during elastic loading.

EXAMPLE 1 ISO 6892-1:2019 A224 defines a test based on strain rate, using ranges 2, 2 and 4.

EXAMPLE 2 ISO 6892-1:2019 B30 defines a test based on stress rate, performed at a nominal stress rate of $30\ MPa\ s^{-1}$.

EXAMPLE 3 ISO 6892-1:2019 B defines a test based on stress rate, performed at a nominal stress rate according to [Table 3](#).

11 Determination of the upper yield strength

R_{eH} may be determined from the force-extension curve or peak load indicator and is defined as the maximum value of stress prior to the first decrease in force. The value is calculated by dividing this force by the original cross-sectional area of the test piece, S_0 (see [Figure 2](#)).

12 Determination of the lower yield strength

R_{eL} is determined from the force-extension curve and is defined as the lowest value of stress during plastic yielding, ignoring any initial transient effects. The value is calculated by dividing this force by the original cross-sectional area of the test piece, S_0 (see [Figure 2](#)).

In case of materials having yield phenomena and when A_e is not to be determined: for productivity of testing, R_{eL} may be reported as the lowest stress within the first 0,25 % strain after R_{eH} , not taking into account any initial transient effect. After determining R_{eL} by this procedure, the test rate may be increased as per [10.3.2.4](#) or [10.3.3.3](#). Use of this shorter procedure should be recorded on the test report.

13 Determination of proof strength, plastic extension

13.1 R_p is determined from the force-extension curve by drawing a line parallel to the linear portion of the curve and at a distance from it equivalent to the prescribed plastic percentage extension, e.g. 0,2 %. The point at which this line intersects the curve gives the force corresponding to the desired proof strength plastic extension. The latter is obtained by dividing this force by the original cross-sectional area of the test piece, S_0 (see [Figure 3](#)).

If the straight portion of the force-extension curve is not clearly defined, thereby preventing drawing the parallel line with sufficient precision, the following procedure is recommended (see [Figure 6](#)).

When the presumed proof strength has been exceeded, the force is reduced to a value equal to about 10 % of the force obtained. The force is then increased again until it exceeds the value obtained originally. To determine the desired proof strength, a line is drawn through the hysteresis loop. A line is then drawn parallel to this line, at a distance from the corrected origin of the curve, measured along the abscissa, equal to the prescribed plastic percentage extension. The intersection of this parallel line and the force-extension curve gives the force corresponding to the proof strength. The value is calculated by dividing this force by the original cross-sectional area of the test piece, S_0 (see [Figure 6](#)).

NOTE Several methods can be used to define the corrected origin of the force-extension curve. One of these is to construct a line parallel to that determined by the hysteresis loop so that it is tangential to the force-extension curve. The point where this line crosses the abscissa is the corrected origin of the force-extension curve (see [Figure 6](#)).

Care should be taken to ensure that the hysteresis is performed after the final proof strength has passed, but at as low an extension as possible, as performing it at excessive extensions will have an adverse effect on the slope obtained.

If not specified in product standards or agreed by the customer, it is inappropriate to determine proof strength during and after discontinuous yielding.

13.2 The property may be obtained without plotting the force-extension curve by using automatic devices (microprocessor, etc.) (see [Annex A](#)).

NOTE Another available method is described in GB/T 228121.

14 Determination of proof strength, total extension

14.1 R_t is determined on the force-extension curve, taking [10.2](#) into consideration, by drawing a line parallel to the ordinate axis (force axis) and at a distance from this equivalent to the prescribed total percentage extension. The point at which this line intersects the curve gives the force corresponding to the desired proof strength. The value is calculated by dividing this force by the original cross-sectional area of the test piece, S_0 (see [Figure 4](#)).

14.2 The property may be obtained without plotting the force-extension curve by using automatic devices (see [Annex A](#)).

15 Method of verification of permanent set strength

The test piece is subjected to a force corresponding to the specified stress for 10 s to 12 s. This force is obtained by multiplying the specified stress by the original cross-sectional area of the test piece, S_0 . After removing the force, it is then confirmed that the permanent set extension or elongation is not more than the percentage specified for the original gauge length; see [Figure 5](#).

NOTE This is a pass/fail test, which is not normally performed as a part of the standard tensile test. The stress applied to the test piece and the permissible permanent set extension or elongation are specified either by the product specification or the requester of the test. Example: Reporting " $R_{t0.5} = 750$ MPa Pass" indicates that a stress of 750 MPa was applied to the test piece and the resulting permanent set was less than or equal to 0,5 %.

16 Determination of the percentage yield point extension

For materials that exhibit discontinuous yielding, A_p is determined from the force-extension curve by subtracting the extension at R_{eH} from the extension at the start of uniform work-hardening. The extension at the start of uniform work-hardening is defined by the intersection of a horizontal line through the last local minimum point, or a regression line through the range of yielding, prior to uniform work-hardening and a line corresponding to the highest slope of the curve occurring at the start of uniform work-hardening (see [Figure 7](#)). It is expressed as a percentage of the extensometer gauge length, L_e .

The method used [see [Figure 7](#) a) or b)] should be documented in the test report.

17 Determination of the percentage plastic extension at maximum force

The method consists of determining the extension at maximum force on the force-extension curve obtained with an extensometer and subtracting the elastic strain.

Calculate the percentage plastic extension at maximum force, A_g , from [Formula \(3\)](#):

$$A_g = \left(\frac{\Delta L_m}{L_e} - \frac{R_m}{m_E} \right) \cdot 100 \quad (3)$$

where

ΔL_m is the extension at maximum force;

L_e is the extensometer gauge length;

R_m is the tensile strength;

m_E is the slope of the elastic part of the stress-percentage extension curve.

NOTE For materials which exhibit a plateau at maximum force, the percentage plastic extension at maximum force is the extension at the mid-point of the plateau (see [Figure 1](#)).

18 Determination of the percentage total extension at maximum force

The method consists of determining the extension at maximum force on the force-extension curve obtained with an extensometer.

Calculate the percentage total extension at maximum force, A_{gt} , from [Formula \(4\)](#):

$$A_{gt} = \frac{\Delta L_m}{L_e} \cdot 100 \quad (4)$$

- d) type of test piece;
- e) location and direction of sampling of test pieces, if known;
- f) testing control mode(s) and testing rate(s) or testing rate range(s) (see [10.3.1](#)) if different from the recommended methods and values given in [10.3.2](#) and [10.3.3](#);
- g) test results:
 - results should be rounded (according to ISO 80000-1) to the following precisions or better, if not otherwise specified in product standards: strength values, in megapascals, to the nearest whole number;
 - percentage yield point extension values, $A_{p0.2}$ to the nearest 0,1 %;
 - all other percentage extension and elongation values to the nearest 0,5 %;
 - percentage reduction of area, Z , to the nearest 1 %.

23 Measurement uncertainty

23.1 General

Measurement uncertainty analysis is useful for identifying major sources of inconsistencies of measured results.

Product standards and material property databases based on this document and earlier editions of ISO 6892 have an inherent contribution from measurement uncertainty. It is therefore inappropriate to apply further adjustments for measurement uncertainty and thereby risk failing product which is compliant. For this reason, the estimates of uncertainty derived by following this procedure are for information only.

23.2 Test conditions

The test conditions and limits defined in this document shall not be adjusted to take account of uncertainties of measurement.

23.3 Test results

The estimated measurement uncertainties shall not be combined with measured results to assess conformance to product specifications.

For consideration of uncertainty, see Annexes K and L, which provide guidance for the determination of uncertainty related to metrological parameters and values obtained from the interlaboratory tests on a group of steels and aluminium alloys.

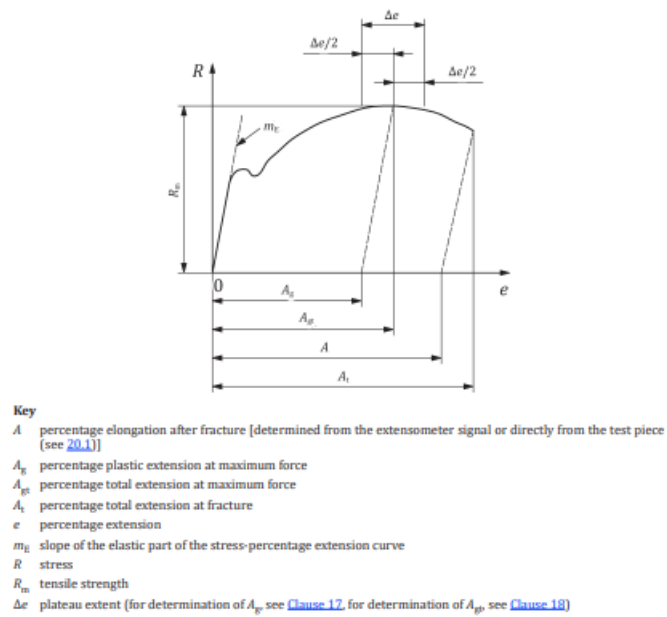
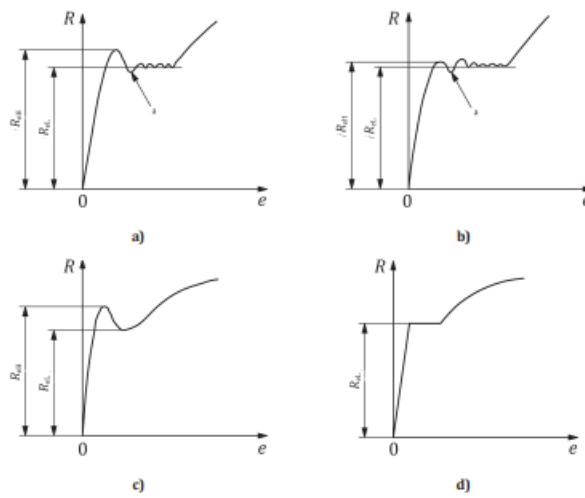
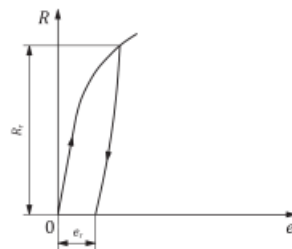


Figure 1 — Definitions of extension



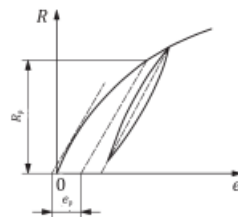
Key
 e percentage extension
 R stress
 R_{uH} upper yield strength
 R_{uL} lower yield strength
 a initial transient effect.

Figure 2 — Examples of upper and lower yield strengths for different types of curve



Key
 e percentage elongation or percentage extension
 e_r percentage permanent set extension or elongation
 R stress
 R_r specified permanent set strength

Figure 5 — Permanent set strength, R_r



Key
 e percentage extension
 e_p specified percentage plastic extension
 R stress
 R_p proof strength, plastic extension

Figure 6 — Proof strength, plastic extension, R_p , alternative procedure (see 13.1)

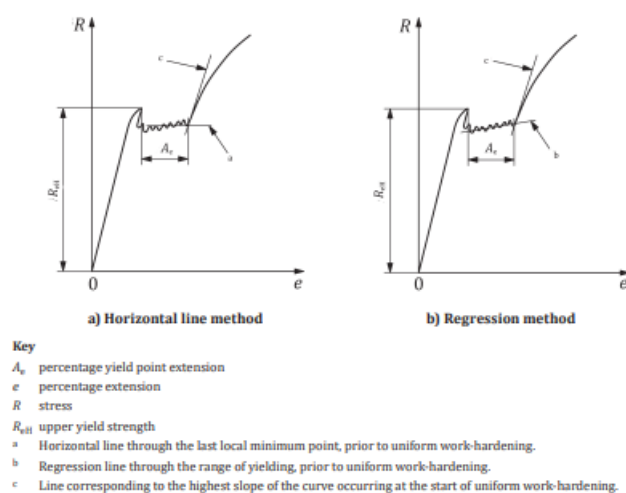
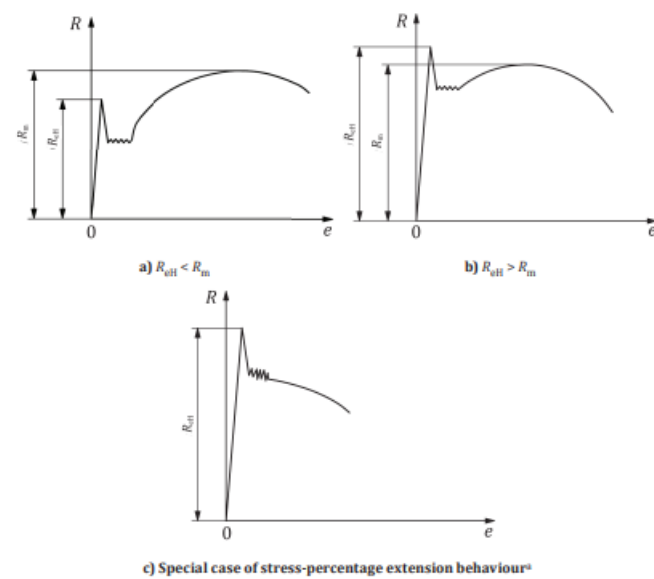


Figure 7 — Different evaluation methods for percentage yield point extension, A_e



Key

e percentage extension

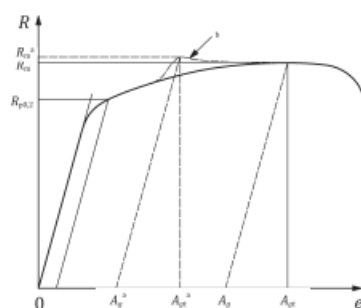
R stress

$R_{0.01}$ upper yield strength

R_m tensile strength

^a For materials which display this behaviour, no tensile strength is defined according to this document. If necessary, separate agreements can be made between the parties concerned.

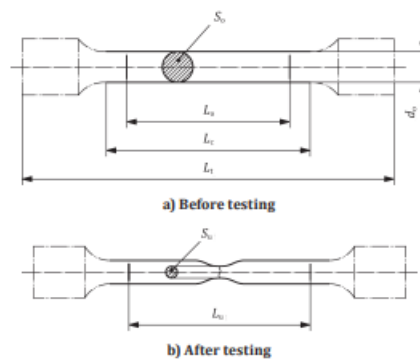
Figure 8 — Different types of stress-extension curve for determination of tensile strength, R_m



Key
 e percentage extension
 R stress
 a False values, resulting from an abrupt strain rate increase.
 b Stress-strain behaviour, if strain rate is abruptly increased.

NOTE For parameter definitions, see [Table 1](#).

Figure 10 — Illustration of an inadmissible discontinuity in the stress-strain curve



Key
 d_o original diameter of the parallel length of a circular test piece
 L_e parallel length
 L_o original gauge length
 L_t total length of test piece
 L_f final gauge length after fracture
 S_o original cross-sectional area of the parallel length
 S_u minimum cross-sectional area after fracture

NOTE The shape of the test-piece heads is only given as a guide.

Figure 13 — Machined test pieces of round cross-section (see Annex D)

Annex A (informative)

Recommendations concerning the use of computer-controlled tensile testing machines

A.1 General

This annex contains additional recommendations for the determination of mechanical properties by using a computer-controlled tensile testing machine. In particular, it provides the recommendations that should be taken into account in the software and testing conditions.

These recommendations are related to the design, the software of the machine and its validation, and to the operating conditions of the tensile test.

A.2 Tensile testing machine

A.2.1 Design

The machine should be designed in order to provide outputs giving analogue signals untreated by the software. If such outputs are not provided, the machine manufacturer should give raw digital data with information on how these raw digital data have been obtained and treated by the software. They should be given in basic SI units relating to the force, the extension, the crosshead separation, the time, and the test piece dimensions. An example of the format of suitable data files is given in [Figure A.1](#).

A.3.7 Measurement of the slope of the curve in the elastic range

In order to be valid for test pieces of unknown characteristics, the method used should not rely upon any predefined stress limit, unless this is defined in the product standard or by agreement between parties to the test.

Methods based on the calculation of the characteristics of a sliding segment are the most convenient. The parameters are the following:

- the length of the sliding segment (number of points used);
- the formula chosen as reference to define the slope of the curve.

NOTE If the straight portion of the force extension curve is not clearly defined, refer to 13.1.

The slope of the curve in the elastic range corresponds to the mean slope in a range where the following conditions are fulfilled:

- the slope of the sliding segment is constant;
- the selected range is representative.

In any case, it is recommended that pertinent limits for the range can be selected by the user in order to eliminate unrepresentative values of the slope of the curve in the elastic range.

References to these and other acceptable methods are given in References [5], [17], [18], and [19].

A recommended method to determine the slope of the elastic line for evaluation of $R_{p0.2}$ (Reference [20]) is given below.

- linear regression of the linear range;
- lower limit: ~10 % of $R_{p0.2}$;
- upper limit: ~40 % of $R_{p0.2}$;
- to get more exact data for $R_{p0.2}$, the elastic line should be checked and if necessary recalculated with other limits.

A.4 Validation of the software for determination of the tensile properties

The efficiency of the methods used by the testing system to determine the various material characteristics may be checked by comparison with results determined in the traditional manner by examination/calculation from plots of analogue or digital data. Data which are derived directly from the machine transducers or amplifiers should be collected and processed using equipment with frequency bandwidth, sampling frequency, and uncertainty of at least equal to those used to provide the machine computer-calculated results.

Confidence may be placed in the accuracy of the machine computer processing if differences in arithmetic means between computer-determined values and those determined manually on the same test piece are small. For the purposes of assessing the acceptability of such differences, five similar test pieces should be tested and the average difference for each relevant property should lie within the limits shown in Table A.1.

NOTE This procedure confirms only that the machine finds the material characteristics for the particular test piece shape, material tested, and conditions used. It gives no confidence that the properties of the material tested are either correct or fit for purpose.

If other methods are used, e.g. injection of a pre-determined set of data from a known material with a recognized level of quality assurance, these should meet the criteria mentioned above and those in Table A.1.

As part of the EU-funded TENSTAND project (GBRD-CT-2000-00412), ASCII data files were produced with agreed values of tensile properties that may be used for validation of software. Further details are given in References [21] and [22].

Table A.1 — Maximum permitted differences between computer-derived and manually derived results

Parameter	D^a		s^b	
	Relative ^c	Absolute ^c	Relative ^c	Absolute ^c
$R_{m0.2}$	≤0,5 %	2 MPa	≤0,35 %	2 MPa
R_{m1}	≤0,5 %	2 MPa	≤0,35 %	2 MPa
R_{mH}	≤1 %	4 MPa	≤0,35 %	2 MPa
R_{mL}	≤0,5 %	2 MPa	≤0,35 %	2 MPa
R_m	≤0,5 %	2 MPa	≤0,35 %	2 MPa
A	—	≤2 %	—	≤2 %

^a $D = \frac{1}{n} \sum_{i=1}^n D_i$.

^b $s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (D_i - D)^2}$.

where

D_i is the difference between the result of manual evaluation, H_p , and the result of computer evaluation, R_p , for a test piece ($D_i = H_i - R_i$);

n is the number of identical test pieces from one sample (≥5);

^c The highest of the relative and absolute values should be taken into account.

A.5 Computer compatible representation of standards

Computer Compatible Representation of Standards Computer readable data formats developed within the scope of the CEN/WS ELSSI-EMD offer an effective means to overcome systems interoperability issues and enable electronic reporting in the engineering materials sector. The findings of CEN/WS ELSSI-EMD, which aimed to establish the viability of defining data formats based on documentary Standards for mechanical testing, are reported in CWA 16200[42]. The guidelines that CWA 16200 describes for defining computer readable data formats based on a documentary testing standard have been applied to ISO 6892-1. The resulting definitions are available from the BSI Standards Resources server.

To demonstrate potential usage, CWA 16200 includes examples of the reporting capability for the data formats based on a tensile test carried out using a test piece manufactured from the Tensile Certified Reference Material CRM 661 (INGELBRECHT and LOVEDAY 2000[43]) carried out as part of the TENSTAND Project (RIDES and LORD, 2005[24]).

D.3.2 Machining tolerances

The value given in Table D.3, e.g. $\pm 0,03$ mm for a nominal diameter of 10 mm, means that no test piece shall have a diameter outside the two values given below, if the nominal value of the original cross-sectional area, S_0 , is to be used in the calculation of results without having to measure each test piece.

- $10 \text{ mm} + 0,03 \text{ mm} = 10,03 \text{ mm}$
- $10 \text{ mm} - 0,03 \text{ mm} = 9,97 \text{ mm}$

D.3.3 Tolerances on shape

The value given in Table D.3 means that, for a test piece with a nominal diameter of 10 mm which satisfies the machining conditions given above, the deviation between the smallest and largest diameters measured shall not exceed 0,04 mm.

Consequently, if the minimum diameter of this test piece is 9,99 mm, its maximum diameter shall not exceed $9,99 \text{ mm} + 0,04 \text{ mm} = 10,03 \text{ mm}$.

Table D.3 — Tolerances relating to the transverse dimensions of test pieces

Dimensions and tolerances in millimetres

Designation	Nominal transverse dimension	Machining tolerance on the nominal dimension ^a	Tolerance on shape ^b
Diameter of machined test pieces of circular cross-section and transverse dimensions of test pieces of rectangular cross-section machined on all four sides	≥ 3	$\pm 0,02$	0,03
	≤ 6		
	> 6	$\pm 0,03$	0,04
	≤ 10		
	> 10	$\pm 0,05$	0,04
	≤ 18		
Transverse dimensions of test pieces of rectangular cross-section machined on only two opposite sides	> 18	$\pm 0,10$	0,05
	≤ 30		
	≥ 3	$\pm 0,02$	0,03
	≤ 6		
	> 6	$\pm 0,03$	0,04
	≤ 10		
	> 10	$\pm 0,05$	0,06
	≤ 18		
	> 18	$\pm 0,10$	0,12
	≤ 30		
	> 30	$\pm 0,15$	0,15
	≤ 50		

^a These tolerances are applicable if the nominal transverse dimensions of machined test piece are to be used in the calculation of the original cross-sectional area, S_0 , without having to measure the transverse dimensions of each test piece. If these machining tolerances are not complied with, it is essential to measure every individual test piece.

^b Maximum deviation between the measurements of a specified transverse dimension along the entire parallel length, L_0 , of the test piece.

Annex G (normative)

Determination of the modulus of elasticity of metallic materials using a uniaxial tensile test

G.1 Background

Although ISO 6892-1 requires the generation of a straight line with a given offset parallel to the linear region of the stress-strain curve in order to determine the specified proof strength, R_p , of the material being tested, most users usually assume that the slope of the linear elastic region of the stress-strain curve corresponds to the modulus of elasticity of the material being tested since the modulus of elasticity, E , is given by the relationship $E = \text{stress/strain}$. However, in general, the Class 1 extensometer required for the tensile test is not sufficiently accurate for measuring the very small strains in the elastic region with sufficient precision to give modulus values with an acceptable level of uncertainty.

It is not required to use this annex to determine the slope of the elastic part of the stress-percentage extension curve for the determination of proof strength.

An additional description of the determination of the modulus of elasticity by tensile testing is given in ASTM E 111^[54]. For information, see also SEP 1235^[44].

G.2 General

This annex contains additional requirements for the determination of the modulus of elasticity using a uniaxial tensile test. This test method is limited to materials which meet the following criteria:

- negligible creep effects of the material in the evaluation range;
- sufficient straight line in the elastic range of the material in the evaluation range.

These requirements are related to the design of the testing equipment, the test piece and the evaluation of the test.

The modulus of elasticity is a characteristic material property and is used for the calculation of the elasticity of products and components conforming to Hooke's Law.

NOTE Typically, this test is performed as a separate test from the tensile test because of the limitation of the extensometer displacement.

G.3 Testing equipment

G.3.1 Accuracy of the testing equipment

G.3.1.1 Force-measuring device

The force-measuring system of the testing machine shall be in accordance with ISO 7500-1, class 1, in the relevant range.

G.3.1.2 Extensometer system

The extensometer system shall be in accordance with ISO 9513, class 0,5, in the relevant range.

The strain shall be measured on opposite sides of the test piece.

The use of a large extensometer gauge length (e.g. ≥ 50 mm) is recommended.

G.3.1.3 Resolution of the testing system

The resolution of the testing system shall be sufficient for obtaining at least 50 different discrete measured values in the evaluation range.

G.3.1.4 Measuring devices for the determination of the relevant test piece dimensions

All measuring devices used for the determination of the original cross-sectional area shall be calibrated to the appropriate standards with traceability to a national measurement system. The measuring device shall be able to guarantee an accuracy of the measured data of better than $\pm 0,5$ % of the measured value.

G.3.2 Method of gripping and alignment

The method of gripping and the alignment are important for the determination of the modulus of elasticity. For requirements regarding the method of gripping, see [10.2](#), and for further information, see ASTM E1012. Additional helpful information may be in ISO 23788.

It is recommended to use mechanical devices (e.g. stoppers) to position the test piece so that good alignment is achieved.

G.4 Test pieces

G.4.1 General

The test pieces shall be straight.

NOTE Bent or twisted test pieces cannot be tested according to this annex.

The test piece surface shall be in such a condition that it does not influence the test result.

Where residual stresses are present in the sample, as a result of either prior processing or sample preparation, the modulus values determined are sometimes not representative of the base material.

G.4.2 Determination of original cross-sectional area

For the determination of the original cross-sectional area, see [Clause 7](#). In addition to the requirements in [Clause 7](#), a minimum of three measurements for each dimension shall be performed. The original cross-sectional area, S_0 , is the average cross-sectional area and shall be calculated from the measurements of the appropriate dimensions. The original cross-sectional area shall be determined with an accuracy of $\pm 0,5$ % or better.

G.5 Procedure

G.5.1 General

If the stress-strain curve up to R_{eH} or $R_{p0,2}$ is not known, a pre-test in advance of the measurement of the modulus of elasticity shall be performed.

G.5.2 Setting the force zero point

The setting of the force zero point shall be carried out in accordance with [10.1](#).

G.5.3 Testing conditions

G.5.3.1 Testing rate

Compared to the other properties determined within the tensile test, the modulus of elasticity is less sensitive to the testing rate. The testing rate should be according to Method A Range 1. Other testing rates including the use of Method B are permitted.

The testing rate may be low to achieve the required number of data points for the analysis.

A constant crosshead separation rate may be used to avoid any discontinuities.

G.5.3.2 Data sampling frequency

The data sampling frequency shall be chosen in such a way that a minimum of 50 measured values is obtained in the relevant range (R_1, R_2).

The minimum data sampling frequency can be calculated by [Formula \(G.1\)](#):

$$f = \frac{N \cdot E \cdot \dot{\epsilon}}{R_2 - R_1} \quad (\text{G.1})$$

where N is the number of measured values in the relevant range.

For steel with $R_1 = 10$ MPa and $R_2 = 50$ MPa and a testing rate of $0,000\,07\text{ s}^{-1}$, the data sampling frequency shall be greater than 18 Hz.

G.5.3.3 Testing procedure

If the test piece will be used more than one time for the modulus determination, the applied load shall not be greater than a value corresponding to 50 % of the expected R_{eH} or $R_{p0,2}$.

Otherwise, it is recommended to perform the test up to a point where plastic deformation can be observed.

G.6 Evaluation

G.6.1 Averaging the extensometry signals

The average strain, necessary for the calculation in [G.6.2](#), is calculated for each stress value by averaging the strain from the opposite sides of the test piece.

Strain data from each side of the test piece may be displayed and differences in the slope of the two curves may be reduced by optimizing the testing equipment (reducing of bending). For further information, see ASTM E 1012. Additional helpful information can be found in ISO 23788.

G.6.2 Calculation of the modulus of elasticity

For evaluation of the recorded data, the following interactive method is recommended.

The method is based on a numerical determination of the line of best fit for the elastic range (least squares method) including a visual evaluation of the match between this line of best fit and the curve of actual measurement readings, followed by recalculation with altered parameters, where appropriate. Therefore, it corresponds essentially to a manual analysis of an X-Y graph.

The use of this method depends on the availability of suitable computer software.

A linear regression of stress over strain (G.4) shall be carried out between a lower stress value R_1 and an upper stress value R_2 (alternatively, strain values e_1 and e_2 may be used):

$$R = \frac{E \cdot e}{100 \%} + b \quad (\text{G.2})$$

where

- R is the stress in megapascals;
- E is the modulus of elasticity in megapascals;
- e is the percentage extension in percent;
- b is the stress offset in megapascals.

The straight line determined in this way shall be drawn into the stress-strain diagram, whereas the initial part of this diagram is magnified for this purpose. The match between the straight line and the curve shall be evaluated visually. It can be useful to consider the coefficient of determination R^2 , which should be close to 1 ($>0,999\ 5$), whereby the number of considered data points should be at least 50.

Another helpful tool is the calculation of the relative standard deviation. The relative standard deviation takes into account the coefficient of determination R^2 and the number of considered data points among other statistical data. It should be less than 1 %.

By shifting the lower or upper values and re-calculating the formula accordingly, the line of best fit (i.e. the modulus of elasticity) can be adapted to the curve.

The following values are recommended as starting points for the regression calculation:

- lower stress value R_1 : $\approx 10\ %$ of R_{eH} or $R_{p0,2}$;
- upper stress value R_2 : $\approx 40\ %$ of R_{eH} or $R_{p0,2}$.

Additionally, the strain offset can be calculated according to Formula (G.3):

$$x_{(y=0)} = \frac{-b}{E} \quad (\text{G.3})$$

Under optimal testing conditions, the chosen default values will not have a great influence on the result of the calculation. Example: if the material fulfils the general conditions described in G.2 and the determined default values R_1 and R_2 are 10 % and 40 % of R_{eH} or $R_{p0,2}$, respectively, a re-calculation of the formula by using default values inside the determined interval (e.g. 10 % to 20 %, 20 % to 30 %, 30 % to 40 % of R_{eH} or $R_{p0,2}$, respectively) will not influence the result significantly.

In cases where the material exhibits no straight elastic line, e.g. cast iron, or the data for the regression is not of sufficient quality, i.e. $R^2 < 0,999\ 5$, the modulus of elasticity should not be determined.

It is recommended to perform regular checks on the repeatability of the results using suitable reference test pieces in the configuration used for testing.

Suitable reference test pieces can be manufactured in-house and should have the same geometry as the test pieces.

Further mathematical approaches and computer analysis methods are available for the evaluation of the modulus of elasticity.

G.7 Measurement uncertainty

G.7.1 General

The estimation of the measurement uncertainty for a determined modulus of elasticity can be done according to CWA 15261-2:2005, A.5^[2] or according to [Annex K](#).

NOTE The estimation of the measurement uncertainty according to CWA 15261-2 is based on absolute values. This results in different estimations of the respective single uncertainty budgets, if e.g. the test piece dimensions or the extensometer gauge length differ. The estimation of the measurement uncertainty according to [Annex K](#) is based on relative estimations. Therefore, the relative estimations normally will not change. Exception is the relative measurement uncertainty budget for the strain measurement. Because of the small extensions during the test in the elastic part, the absolute uncertainty of the strain measurement is relevant for the uncertainty contribution (according to ISO 9513).

G.7.2 Estimation of the measurement uncertainty according to CWA 15261-2

G.7.2.1 General

NOTE In CWA 15261-2, the symbol L_e is used for the gauge length and m_E for the slope of the elastic part of the force-extension curve. For conformation with this document and to prevent confusion in the following (differing from CWA), the symbol L_o is used for the extensometer gauge length and S_E for the slope of the elastic part of the force-extension curve.

The measurement uncertainty according to CWA 15261-2 is given by [Formula \(G.4\)](#):

$$u_c(E) = \sqrt{\left(\frac{L_o}{S_o}\right)^2 \cdot u^2(S_E) + \left(\frac{S_E}{S_o}\right)^2 \cdot u^2(L_o) + \left(\frac{S_E L_o}{S_o^2}\right)^2 \cdot u^2(S_o)} \quad (G.4)$$

where

- L_o is the extensometer gauge length;
- S_o is the original cross-sectional area;
- S_E is the slope of the force-extension curve;
- $u(S_E)$ is the uncertainty of slope of the force-extension curve;
- $u(L_o)$ is the uncertainty of extensometer gauge length;
- $u(S_o)$ is the uncertainty of original cross-sectional area.

G.7.2.2 Example for the calculation of the measurement uncertainty

[Table G.1](#) shows the results of an example for the measurement uncertainty according to CWA 15261-2 for a measured modulus of elasticity of 186,7 GPa^[24] based on the following data:

L_o :	50 mm
S_o :	78,5 mm ²
S_E :	293,07 kN/mm
$u(L_o)$:	0,144 mm
$u(S_o)$:	0,785 mm ²
$u(S_E)$:	0,064 kN/mm

Table G.1 — Uncertainty contribution, example 1 according to CWA 15261-2

Parameter	Sensitivity coefficients ^a	Uncertainty contribution ^a
$\frac{L_e}{S_0}$	0,637 mm ⁻¹	
$u(S_E)$		0,064 $\frac{\text{kN}}{\text{mm}}$
$\frac{S_E}{S_0}$	3,733 $\frac{\text{kN}}{\text{mm}^3}$	
$u(L_e)$		0,144 mm
$-\frac{S_E L_e}{S_0^2}$	-2,378 $\frac{\text{kN}}{\text{mm}^4}$	
$u(S_0)$		0,785 mm ²
$u_c(E)^b$		1,9 $\frac{\text{kN}}{\text{mm}^2}$

^a Values are given for information only.

^b $u_c(E)$ is calculated according to [Formula \(G.5\)](#).

$$u_c(E) = \sqrt{0,637^2 \cdot 0,064^2 + 3,733^2 \cdot 0,144^2 + (-2,378)^2 \cdot 0,785^2} = 1,9 \text{ GPa} \quad (\text{G.5})$$

For a 95 % level of confidence, the combined uncertainty shall be multiplied by a coverage factor, $k = 2$ [see [Formula \(G.6\)](#)].

$$U(E) = k \cdot u_c(E) = 2 \cdot 1,9 \text{ GPa} = 3,8 \text{ GPa} \quad (\text{G.6})$$

This is 2,0 % based on the modulus of elasticity of 186,7 GPa.

The result of the test for the modulus of elasticity is: 186,7 GPa $\pm$ 3,8 GPa ($k = 2$, 95 % confidence level).

That means that, with a confidence level of 95 %, the true value for the modulus of elasticity is in the range between 182,9 GPa and 190,5 GPa.

G.7.3 Estimation of the measurement uncertainty according to [Annex K](#)

[Table G.2](#) indicates the uncertainty contribution that should be considered for the modulus of elasticity according to [Annex K](#).

Table G.2 — Uncertainty contribution, example 2 according to Annex K

Parameter	Uncertainty contribution ^a %
Standard deviation of slope $S_{m(m)}$	0,2
Standard deviation of X-values of the X-Y graph, $S_x^{b,c}$	3
Standard deviation of Y-values of the X-Y graph, S_y	1
Extensometer gauge length, L_e	0,5
Original cross-sectional area, S_a	1
^a Values are given for information only.	
^b S_m consists of S_x and S_y , therefore S_x and S_y should be considered.	
^c Based on the small extensions measured in the test, the absolute value (1,5 µm of a class 0,5 extensometer) has to be used. Example: $\Delta R = 200$ MPa, $E = 200$ GPa, $L_e = 50$ mm results in an extension of 0,05 mm. By using the bias error of 1,5 µm (absolute value of an 0,5 class extensometer), the uncertainty contribution is 3 %.	

The combined uncertainty for the modulus of elasticity, expressed as a percentage, is given by [Formula \(G.7\)](#).

$$u_c(E) = \sqrt{\left(\frac{0,2}{\sqrt{3}}\right)^2 + \left(\frac{3}{\sqrt{3}}\right)^2 + \left(\frac{1}{\sqrt{3}}\right)^2 + \left(\frac{0,5}{\sqrt{3}}\right)^2 + \left(\frac{1}{\sqrt{3}}\right)^2} = 1,9\% \quad (G.7)$$

For a 95 % level of confidence, the combined uncertainty shall be multiplied by a coverage function, $k = 2$ [see [Formula \(G.8\)](#)].

$$U(E) = k \cdot u_c(E) = 2 \cdot 1,9\% = 3,8\% \quad (G.8)$$

The result of the test for the modulus of elasticity is: (186,7 ± 7,1) GPa ($k = 2$, 95 % confidence level).

This means that, with a confidence level of 95 %, the true value for the modulus of elasticity is in the range between 179,6 GPa and 193,8 GPa.

G.7.4 Proficiency test

A proficiency test "Young's Modulus" was performed and the measurement uncertainty for all participants was determined. An measurement uncertainty for the determination of the modulus of elasticity between 1,2 % and 5 % (at 95 % confidence level) is appropriate^[24].

G.8 Test report

The test report shall contain the information required in [Clause 22 a\)](#) to f). Furthermore, the following information shall be included:

- type of extensometer system;
- default stress values R_1 and R_2 (in MPa) or the default strain values e_1 and e_2 (in %), respectively;
- number of measured values in the evaluation range (between R_1 and R_2 or e_1 and e_2);
- modulus of elasticity E (in GPa), which should be rounded to the nearest 0,1 GPa according to ISO 80000-1;
- measurement uncertainty including level of confidence (in GPa) and the method of determination (CWA 15261-2:2005, A.5 or [Table G.2](#));
- coefficient of determination R^2 of the best fit of the straight line or standard deviation S_m (in GPa) or relative standard deviation $S_{m(rv)}$ (in %).

G.9 Additional considerations

In general, it is difficult to determine reliable values of modulus in the tensile test unless special high resolution averaging extensometer systems are employed, and such devices are not generally suitable for covering the full range of the tensile test. If a single sided extensometer or clip gauge is employed, then any slight misalignment of the test piece can result in large errors of the apparent modulus measurement.

G.10 Other methods for determining modulus

The tensile test is not the best method for determining reliable values of modulus of elasticity, and other alternative methods, e.g. impulse excitation or ultrasonics, are preferable. More information can be found in References [42] and [43] to [46].

G.11 Uncertainty and reproducibility

Full uncertainty budgets are not included here but procedures for estimating uncertainty based on the GUM[4] associated with modulus measurements have been developed as part of the European UNCERT project, both for tensile testing[42] and for dynamic measurements[48].

Reproducibility of modulus measurements based on 2 times the standard deviation (s) from a series of tensile test inter-comparison exercises, collated as part of the TENSTAND Project, are summarized in Table G.3[45].

Table G.3 — Overview of round robin tests: modulus of elasticity or slope of the elastic line, respectively

Reference	Authors	Year	Material	Reproducibility ($\pm 2s$) %
Testing Materials of Construction	Unwin[50]	1910	Mild steel	2
VAMAS	Lord, Roebuck and Orkney[51]	1995	SiC/Al MMC	6
BCR Tensile Reference Material CRM 661	Ingelbrecht and Loveday[49]	2000	Nimonic 75	12
TENSTAND WP3 Modulus Measurement	Lord, Rides and Loveday[46]	2005	Various	5–25
TENSTAND WP2 ASCII Data Files	Lord, Loveday, Rides and McEntegart[46]	2005	Various - ASCII datafiles	1–6

The majority of the results reported above were based on the criteria laid down in ISO 6892 or the equivalent earlier standards. It should also be considered that the aim of several tests is the determination of common tensile test properties (e.g. also the generation of ASCII data sets in TENSTAND WP2). So the typically single sided Class 1 extensometers with a limited accuracy in the elastic range were employed and the slope of the elastic part of the stress-percentage extension curve m_E was determined with the aim of evaluation of $R_{p0.2}$ and other properties and not to determine the intrinsic material property modulus of elasticity E . If double sided high resolution Class 0.5 extensometers are used as specified in this annex, the uncertainty of measurement should be less and the reproducibility much better.

Annex K (informative)

Estimation of the uncertainty of measurement

K.1 General

This annex gives guidance on how to estimate the uncertainty of the values determined in accordance with this document. It is not possible to give an absolute statement of uncertainty for this test method because there are both *material independent* and *material dependent* contributions to the uncertainty statement. ISO/IEC Guide 98-3^[4] is a comprehensive document of over 90 pages based upon rigorous statistical methods for the summation of uncertainties from various sources. Its complexity has provided the driving force for a number of organizations to produce simplified versions (see NIS 80^[45], NIS 3003^[46], and Reference [23]). These documents all give guidance on how to estimate uncertainty of measurement based upon an "uncertainty budget" concept. For detailed descriptions, see EN 10291^[44] and Reference [24]. Additional information on the estimation of uncertainty is available in References [25] and [26]. The measurement uncertainty presented here does not describe the scatter resulting from the inhomogeneity of the material, e.g. from one batch, from the beginning and at the end of an extruded profile or a rolled coil, or of different positions within a casting. The uncertainty results from the scatter of the data obtained from different tests, different machines, or different laboratories taken from an ideal homogeneous material. In the following, the different influences are described and guidance for the determination of the uncertainties is given.

The reproducibility values used in Tables K.2 to K.4 are half width intervals in accordance with ISO/IEC Guide 98-3^[4] and should be interpreted as the value of plus and minus ($\pm$) scatter tolerances.

K.2 Estimation of uncertainty

K.2.1 General

The standard uncertainty, u , of the value of a parameter can be estimated in two ways.

K.2.2 Type A — By repeated measurement

$$u = \frac{s}{\sqrt{n}} \quad (\text{K.1})$$

where

s is the standard deviation of the measurements;

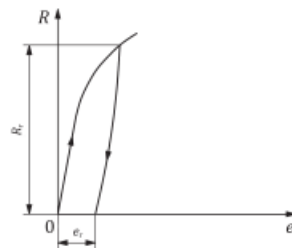
n is the number of observations being averaged to report the result of the measurement under normal circumstances.

K.2.3 Type B — From some other source, e.g. calibration certificates or tolerances

Here, the true value is equally likely to occur anywhere within the defined interval so the distribution is described as rectangular or uniform. Here the standard uncertainty is given by Formula (K.2):

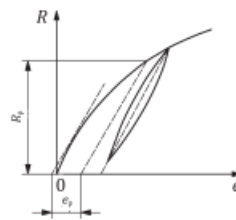
$$u = \frac{a}{\sqrt{3}} \quad (\text{K.2})$$

where a is half the width of the interval in which the quantity is assumed to lie.



Key
 e percentage elongation or percentage extension
 e_r percentage permanent set extension or elongation
 R stress
 R_r specified permanent set strength

Figure 5 — Permanent set strength, R_r

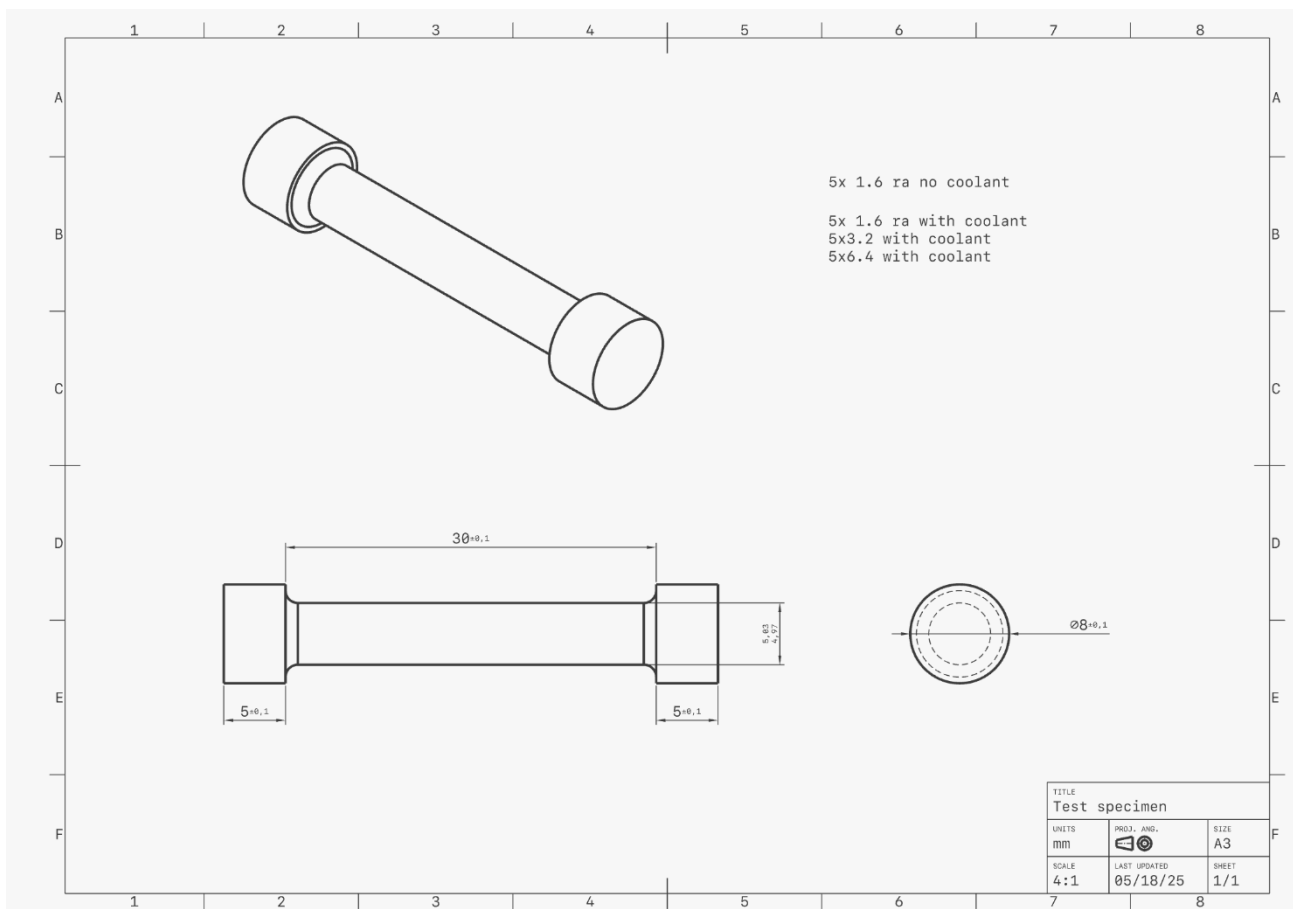


Key
 e percentage extension
 e_p specified percentage plastic extension
 R stress
 R_p proof strength, plastic extension

Figure 6 — Proof strength, plastic extension, R_p , alternative procedure (see 13.1)

10.3 Appendix 3- Orthographic drawing of tensile test specimen (without notch)

This appendix shows the orthographic drawing used to manufacture the test specimens without a notch.



10.4 Appendix 4- Orthographic drawing of tensile test specimen (with notch)

This appendix shows the orthographic drawing used to manufacture the test specimens with the notch.

