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Original Scientific Article

EVALUATION OF THE MECHANICAL PROPERTIES OF STEEL UNDER ELEVATED TEMPERATURE CONDITIONS

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Abstract This paper presents the influence of elevated temperatures on the mechanical properties of steel with varying iron content and alloying compositions. The paper combines chemical analysis and high-temperature tensile testing to examine how microstructure, chemical composition and temperature affect the yield strength, tensile strength and ductility of steel. Samples of two thicknesses (0.63 mm and 0.50 mm) and three iron levels (85 wt%, 90 wt %, and 97 wt%) were analysed and classified based on their chemical composition. Tensile tests were performed in accordance with ISO 6892-2 within the temperature range of 90 °C to 250 °C, using 20 °C increments. The findings highlight the combined effect of temperature and alloying chemistry on the high-temperature performance of steel, providing valuable insights for material selection in thermally demanding engineering applications.

Keywords
steel,
tensile test,
temperature,
chemical analysis,
stress-strain diagram,
alloying elements

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1 Introduction

The field of Materials Science has advanced significantly in recent years, and is becoming increasingly important in engineering and design. Numerous historical examples demonstrate that structural failures under load often occur due to inappropriate material selection [1], resulting in significant financial losses, and, in many cases, fatalities [3]. To prevent such events, a systematic study of materials and their properties began to develop. It became evident that the chemical composition and microstructure of a material determine its properties fundamentally, and that these properties are not constant under all conditions [6].

Understanding material behaviour at different temperatures is essential for the safe design of devices and structures. Many components operate in high-temperature environments or experience considerable heating during service, resulting in significant changes to their mechanical properties. If such changes are not considered properly during the design process, component failure may occur. Conversely, numerous machines and structures operate in environments exposed to low temperatures, where the risk of brittle fracture increases substantially. To prevent such unpredictable failures, the study and testing of materials became necessary. The development of standardised laboratory tests enabled reliable observation of material behaviour under various loads and environmental conditions. This knowledge enabled the selection of appropriate materials, thereby reducing the likelihood of structural failure. Continued research has also led to the development of new alloys and materials with improved properties for specific applications.

For these reasons, the paper investigates the behaviour of the mechanical properties of steel at elevated temperatures. Steel was selected as the test material because it is one of the most widely used engineering materials in industrial applications. The paper is structured into two main parts. The first part outlines the fundamental structure of metals, including their crystal structures and lattice defects, and provides an overview of steel and the key alloying elements that influence its mechanical and chemical properties. The paper also reviews the tensile test, the fundamental method for determining mechanical properties, in accordance with ISO 6892-1 for room-temperature testing and ISO 6892-2 for high-temperature testing. These Standards

ensure reliable and repeatable determination of the characteristic values of metallic materials.
The aim of this paper was to determine how the mechanical properties of steel change with increasing temperature, and how they are affected by the iron content and accompanying alloying elements. These research questions guided the experimental work, which focused on tensile testing. The tests were conducted from 90 °C to 250 °C in increments of 20 °C. Before conducting the tensile tests in accordance with ISO 6892-2, a chemical analysis was performed on all the samples to verify the similarity of their chemical compositions. The samples were then categorised by thickness and iron content, resulting in five test groups.

2 Methodology

2.1 Microstructure of metals: Crystal structure, lattice defects, steel and alloying elements

When a material solidifies, it forms either an amorphous or a crystalline structure. Metals form crystalline structures almost exclusively, where the atoms are arranged in a periodic lattice described by a unit cell [7]. Most metals crystallise in one of three common structures: a face-centred cubic (FCC), hexagonal close-packed (HCP), or body-centred cubic (BCC).

The FCC structure has the highest packing density (74 %) and is characteristic of metals such as aluminium (Al), copper (Cu) and nickel (Ni). In steels, the high-temperature austenite phase also adopts the FCC structure. The HCP structure has the same packing factor but a different geometry, with each atom surrounded by twelve neighbours; this arrangement is typical of metals such as magnesium, titanium and zinc. The BCC structure has a lower packing density (68 %), with atoms touching along the body diagonal of the cube, and is found in α-iron, vanadium, niobium, tungsten and molybdenum [7].

Real crystals are never perfect. Their microstructure contains defects that affect the physical, chemical and mechanical properties significantly. Point defects, such as vacancies, interstitial atoms and substitutional atoms, play a crucial role in diffusion and high-temperature behaviour. Line defects, also referred to as dislocations, enable plastic deformation at much lower stresses than would be required in a perfect lattice

[10]. Planar defects, including stacking faults, coherent interfaces and grain boundaries, influence slip behaviour and phase transformations. Volume defects, such as porosity, inclusions and microcracks, reduce strength and fracture resistance, and are found commonly in cast products [7].

Together, the crystal structure and its defects determine the microstructure of metals and influence their mechanical behaviour significantly under various loading and temperature conditions.

Steel is an alloy of iron that contains small amounts of carbon, typically below 2.06%, together with various alloying elements that improve its mechanical, chemical and physical properties. Carbon is the most influential element, as it governs the formation of ferrite, pearlite, bainite and martensite, and affects the strength, hardness, ductility and weldability strongly. Based on their chemical composition, steels are classified as unalloyed, low-alloyed, high-alloyed, ferritic, or austenitic. By application, they are divided into tool steels, general structural steels, heat-treatable steels and special steels [8].

Austenitic steels contain elements such as manganese, nickel and cobalt, which expand the γ-phase field and stabilise the austenitic structure down to room temperature. They are non-magnetic, corrosion-resistant, and cannot be strengthened by heat treatment; their properties are improved mainly through plastic deformation. Ferritic steels contain elements such as silicon, chromium, molybdenum and titanium, which stabilise the α-phase. They are magnetic and corrosion-resistant, but, like austenitic steels, they cannot be heat-treated, and their practical significance is more limited [9].

The mechanical behaviour of steel is influenced strongly by alloying elements. Carbon increases the strength, hardness and hardenability, but reduces toughness and ductility. Manganese enhances deoxidation and hot workability, while silicon strengthens the ferrite phase and improves oxidation resistance. Elements such as chromium, nickel and molybdenum enhance corrosion resistance, hardenability and high-temperature strength, whereas vanadium, niobium and aluminium contribute to grain refinement and strengthening. Copper increases the corrosion resistance, while phosphorus and sulphur generally reduce ductility and weldability if present in higher amounts [7].

The Fe–C diagram illustrates the primary phase transformations that govern the microstructure and properties of steel. At low temperatures, iron exists as α-ferrite, a BCC phase with extremely low carbon solubility (up to 0.02 wt%) and ferromagnetic behaviour up to the Curie temperature of 768 °C. With increasing temperature, the ferrite transforms into γ-austenite, an FCC phase capable of dissolving up to 0.77 % carbon due to its more open lattice structure. At 723 °C and 0.77 wt% C, steel undergoes a eutectoid reaction, producing pearlite, a lamellar mixture of ferrite and cementite (Fe_3C). Hypoeutectoid steels form ferrite plus pearlite upon cooling, while hypereutectoid steels form pearlite together with secondary cementite. Rapid cooling of austenite produces martensite, a supersaturated and hard tetragonal phase characteristic of quenched high-carbon steels. At a higher carbon content, the system also exhibits a eutectic reaction at 1147 °C and 4.3 wt% C, where the liquid transforms into ledeburite, a mixture of austenite and cementite typical of white cast iron [5].

2.2 Tensile test methods and material response

The tensile test is the fundamental mechanical test used to determine the strength properties of materials. In this test, a sample is loaded uniaxially with a gradually increasing force, allowing determination of the elastic modulus, yield strength, tensile strength and ductility [2]. Standardised sample geometries ensure that a fracture occurs in the gauge section, while enlarged ends allow proper gripping in the testing machine. Temperature control is critical, as tensile tests may be performed at room, elevated, or reduced temperatures. Each temperature regime is governed by specific Standards that define the procedures and permissible gradients. Multiple thermocouples are often used to ensure uniform heating, since temperature variations can affect the stresses a material can withstand significantly. The testing speed also influences the measured properties. Lower strain rates generally produce lower strengths and higher ductility, while higher rates result in the opposite behaviour. Therefore, the test speed must comply with the method or product specification. During testing, the load range must match the expected values, all the measurements must be recorded carefully, and the instruments must be capable of capturing the deformation accurately. Any deviation, such as a non-linear elastic region or a sudden load drop, may indicate improper gripping, sample misalignment, or instrumentation issues. If no such problems occur, the sample is loaded until fracture, and the stress–strain curve is recorded throughout the test [4].

3 Results

This section presents the results of the chemical composition and tensile tests. To ensure the accurate and comparable evaluation of the tensile test results, a chemical analysis was first conducted to categorise the samples based on their iron content. Based on the measured values, the samples were classified into three levels of iron content (85 wt%, 90 wt%, and 97 wt%) and into two thicknesses (0.63 mm and 0.50 mm). Since the measured values varied, an acceptable deviation limit was defined of ±2 mass percent of iron. Tables 1 to 5 present the chemical composition of samples differing in iron content and thickness.

Table 1: Chemical composition of samples with 90 wt% Fe and a thickness of 0.63 mm.

	Si	Al	P	Cu	Cr	Mn	Ni	Mo	S	Ti
Sample 1	4.33	3.55	0.716	0.363	0.255	0.2	0.188	0.047	0.028	0.025
Sample 2	3.747	2.96	0.655	0.322	0.289	0.204	0.184	0.046	0.031	0.023
Sample 3	4.253	3.49	0.774	0.305	0.279	0.227	0.2	0.055	0.036	0.018
Sample 4	3.99	3.253	0.654	0.319	0.263	0.189	0.211	0.047	0.036	0.022
Sample 5	4.183	3.307	0.695	0.327	0.262	0.192	0.204	0.045	0.027	0.023
Sample 6	4.37	3.73	0.734	0.304	0.261	0.209	0.207	0.046	0.03	0.022
Sample 7	4.047	3.27	0.63	0.318	0.265	0.217	0.194	0.047	0.035	0.021
Sample 8	3.973	3.367	0.701	0.314	0.271	0.185	0.199	0.045	0.03	0.021
Sample 9	3.81	2.933	0.62	0.385	0.292	0.174	0.211	0.048	0.036	0.02
Sample 10	4.33	3.55	0.716	0.363	0.255	0.2	0.188	0.047	0.028	0.025

Table 2: Chemical composition of samples with 97 wt% Fe and a thickness of 0.63 mm.

	Si	Al	P	Cu	Cr	Mn	Ni	Mo	S	Ti
Sample 1	1.462	0	0.068	0.818	0.212	0.273	0.286	0.07	0.043	0.008
Sample 2	1.523	0	0.075	0.502	0.212	0.288	0.295	0.07	0.04	0.014
Sample 3	1.387	0	0.066	0.477	0.249	0.257	0.28	0.072	0.05	0
Sample 4	1.413	0	0.066	0.633	0.268	0.276	0.299	0.072	0.054	0.007
Sample 5	1.43	0	0.071	0.473	0.221	0.27	0.287	0.071	0.047	0.004
Sample 6	1.457	0.073	0.071	0.682	0.221	0.261	0.29	0.072	0.044	0.009
Sample 7	1.483	0	0.076	0.5	0.221	0.262	0.293	0.069	0.044	0.01
Sample 8	1.533	0	0.076	0.482	0.211	0.259	0.305	0.07	0.044	0.011
Sample 9	1.363	0	0.07	0.491	0.203	0.261	0.306	0.072	0.043	0.005
Sample 10	1.48	0	0.075	0.481	0.207	0.261	0.3	0.07	0.047	0.013

Table 3: Chemical composition of samples with 90 wt% Fe and a thickness of 0.5 mm.

	Si	Al	P	Cu	Cr	Mn	Ni	Mo	S	Ti
Sample 1	4.097	3.213	0.718	0.516	0.309	0.186	0.206	0.049	0.038	0.028
Sample 2	3.763	2.857	0.645	0.36	0.303	0.162	0.204	0.048	0.04	0.02
Sample 3	5.043	4.297	0.981	0.306	0.286	0.19	0.228	0.05	0.041	0.025
Sample 4	3.717	2.92	0.681	0.308	0.311	0.187	0.207	0.05	0.036	0.018
Sample 5	3.727	3.08	0.708	0.306	0.307	0.16	0.218	0.049	0.036	0.017
Sample 6	3.52	2.65	0.646	0.32	0.311	0.194	0.204	0.048	0.04	0.017
Sample 7	4.347	3.43	0.714	0.433	0.311	0.178	0.216	0.049	0.044	0.025
Sample 8	3.763	2.89	0.624	0.319	0.289	0.179	0.216	0.049	0.033	0.021
Sample 9	3.813	2.93	0.675	0.323	0.311	0.169	0.205	0.049	0.035	0.02
Sample 10	4.633	3.93	0.828	0.296	0.282	0.232	0.197	0.055	0.043	0.017

Table 4: Chemical composition of samples with 97 wt% Fe and a thickness of 0.5 mm.

	Si	Al	P	Cu	Cr	Mn	Ni	Mo	S	Ti
Sample 1	1.303	0.465	0.415	0.347	0.262	0.076	0.042	0.015	0.008	0
Sample 2	1.37	0.46	0.413	0.356	0.256	0.075	0.04	0.003	0.017	0.007
Sample 3	1.487	0.444	0.427	0.333	0.275	0.073	0.036	0.019	0	0
Sample 4	1.433	0.49	0.416	0.347	0.268	0.073	0.044	0.008	0	0
Sample 5	1.35	0.485	0.43	0.357	0.266	0.073	0.039	0.007	0	0.01
Sample 6	1.447	0.47	0.44	0.387	0.257	0.072	0.038	0.013	0	0
Sample 7	1.47	0.484	0.444	0.368	0.287	0.075	0.043	0.008	0	0
Sample 8	1.487	0.503	0.423	0.364	0.268	0.075	0.036	0	0.027	0
Sample 9	1.48	0.474	0.434	0.394	0.238	0.07	0.037	0.011	0	0
Sample 10	1.433	0.463	0.433	0.373	0.273	0.075	0.052	0.013	0	0

Table 5: Chemical composition of samples with 85 wt% Fe and a thickness of 0.63 mm.

	Si	Al	P	Cu	Cr	Mn	Ni	Mo	S	Ti
Sample 1	6.297	5.523	1.2	0.384	0.388	0.257	0.283	0.054	0.044	0.027
Sample 2	5.387	4.823	1.04	0.365	0.385	0.239	0.316	0.059	0.039	0.022
Sample 3	6.52	5.63	1.203	0.393	0.379	0.167	0.273	0.055	0.042	0.022
Sample 4	6.523	5.74	1.227	0.372	0.378	0.244	0.282	0.057	0.048	0.02
Sample 5	6.253	5.543	1.177	0.382	0.377	0.264	0.321	0.058	0.045	0.021
Sample 6	4.633	3.93	0.828	0.296	0.282	0.232	0.197	0.055	0.043	0.017
Sample 7	5.277	4.557	1.017	0.394	0.398	0.267	0.312	0.058	0.042	0.021
Sample 8	6.447	5.58	1.2	0.381	0.381	0.266	0.291	0.058	0.043	0.018
Sample 9	4.747	3.933	0.867	0.285	0.28	0.243	0.204	0.057	0.042	0.027
Sample 10	6.297	5.523	1.2	0.384	0.388	0.257	0.283	0.054	0.044	0.027

Tables 1 to 5 show that the chemical composition within each group of samples is highly homogeneous, as the concentrations of individual elements vary only minimally. This confirms that the material quality within each iron-content group is consistent. The Tables also reveal clear differences between the groups: samples with

97 wt% iron contain only very small amounts of other elements, whereas samples with 90 wt%, and especially 85 wt% iron, exhibit noticeably higher contents of elements such as Si, Al, Mn, or Cr. This indicates that the groups differ primarily in their degree of alloying, which will influence their mechanical behaviour in the tensile tests directly. Figure 1 presents the stress-strain diagram for samples with 90 wt% Fe and a thickness of 0.63 mm.

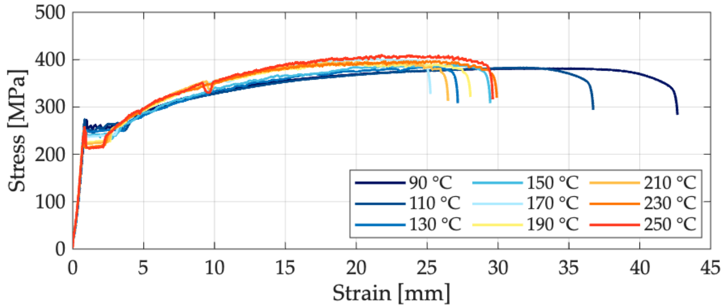


Figure 1: Stress-strain diagram for samples with 90 wt% Fe and a thickness of 0.63 mm.
Source: own.

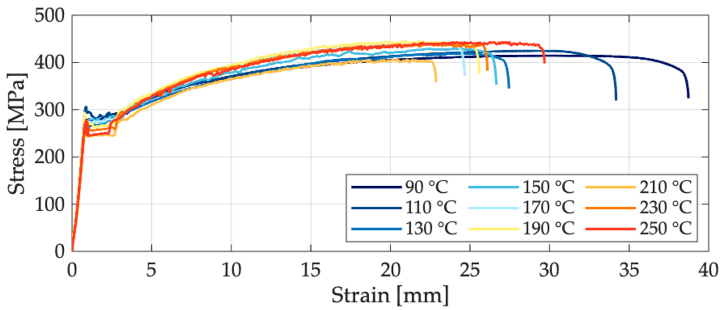


Figure 2: Stress-strain diagram for samples with 97 wt% Fe and a thickness of 0.63 mm.
Source: own.

Figure 1 shows the tensile test results for samples with 90 wt% Fe and a thickness of 0.63 mm. The measurements revealed notable differences that can be linked to the chemical composition. Sample 1, tested at 90 °C, had the lowest elastic modulus but the highest elongation, which corresponds to its low Mo content and higher Si and Ti contents. Sample 2 showed the highest elastic modulus yet the lowest tensile strength, likely due to its reduced Cr content. Sample 3 had the lowest upper yield strength in this group, while sample 4, with higher amounts of P, Mn, and Mo, reached an increased tensile strength but a noticeable drop in elongation. At intermediate temperatures (150–190 °C), variations in the alloying elements resulted in differences primarily in tensile strength and elongation. At higher temperatures (210–250 °C), the elastic modulus continued to decrease, while elongation increased gradually. The highest tensile strength was recorded at 250 °C for sample 10, which also had the highest contents of Cu, Cr, Ni, and S. Figure 2 presents the stress-strain diagram for samples with 97 wt% Fe and a thickness of 0.63 mm.

Figure 2 presents the tensile test results for samples with a composition of 97 wt% Fe and a thickness of 0.63 mm. The results revealed noticeable differences associated with the chemical composition. The sample tested at 90 °C had the lowest Fe content and the highest Cu content, which corresponded to lower tensile strength but the largest elongation in this group. At 110 °C, variations in the Mn, Fe, and Mo contents resulted in a higher yield strength and moderate changes in tensile strength and elongation. As the temperature increased to 130 °C and 150 °C, the elastic modulus rose, while the tensile strength and elongation decreased. At intermediate temperatures (170–190 °C), the samples reached similar, relatively high tensile strengths, with larger differences mainly in the elastic modulus. The sample tested at 210 °C showed the lowest tensile strength, yield strength and elongation, which aligns with its higher Si and P contents. The final samples, tested at 230 °C and 250 °C, exhibited no major differences in mechanical behaviour despite noticeable variations in their chemical composition. Figure 3 presents the stress-strain diagram for samples with 90 wt% Fe and a thickness of 0.5 mm.

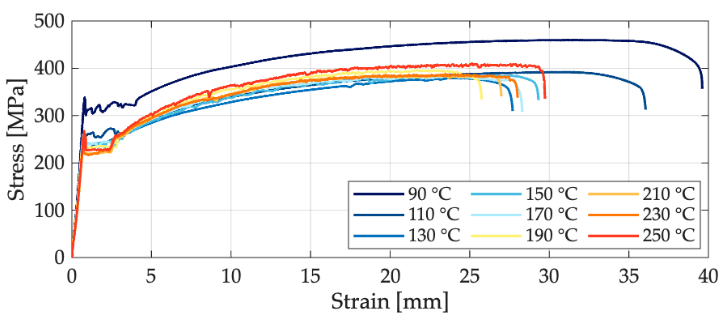


Figure 3: Stress-strain diagram for samples with 90 wt% Fe and a thickness of 0.5 mm.

Source: own.

Figure 3 shows the tensile test results for samples with 90 wt% Fe and a thickness of 0.50 mm. The sample tested at 90 °C clearly stands out, reaching the highest elastic modulus, yield strength, tensile strength and elongation, which corresponds to its higher Cu content. At 110 °C all the mechanical properties dropped sharply, due to the sample's high contents of Si, Al, P, and Mn, known to reduce strength and ductility. At 130 °C, the tensile strength and elongation decreased further. The samples tested at 150 °C and 170 °C showed almost identical behaviour, consistent with their similar chemical composition. At 190 °C, the tensile strength increased slightly, while ductility reached its lowest value because of higher P, S, and Mn contents. The samples tested at 210 °C and 230 °C reached the lowest modulus and yield strength in this group, whereas the sample tested at 250 °C showed a slight recovery in strength due to higher Ni and Mo contents. Figure 4 presents the stress-strain diagram for samples with 97 wt% Fe and a thickness of 0,5 mm.

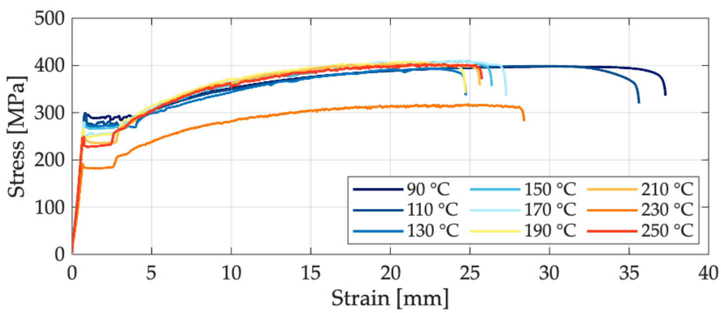


Figure 4: Stress-strain diagram for samples with 97 wt% Fe and a thickness of 0.5 mm.
Source: own.

Figure 4 shows the tensile test results for samples with 97 wt% Fe and a thickness of 0.50 mm. The sample tested at 90 °C reached the highest upper yield strength and elongation in this group, together with moderate values of elastic modulus and tensile strength. Very similar results were obtained at 110 °C and 130 °C, with only a minor increase in the elastic modulus and a more noticeable reduction in elongation at 130 °C, which aligns with their almost identical chemical compositions. At 150 °C and 170 °C, the sample exhibited very similar tensile behaviour, while sample 6 achieved the highest tensile strength and elastic modulus in this group. Between 190 °C and 230 °C, the mechanical properties decreased gradually with the increasing temperature. The sample tested at 190 °C showed the lowest elongation, and, at 230 °C, all the measured properties reached their minimum values. The chemical compositions of these samples differed only slightly. At 250 °C, sample 10 exhibited a small increase in mechanical properties, with no major differences in chemical composition compared to the others. Figure 5 presents the stress-strain diagram for samples with 85 wt% Fe and a thickness of 0.63 mm.

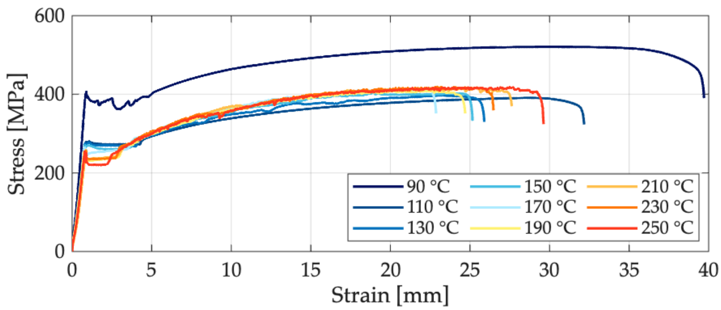
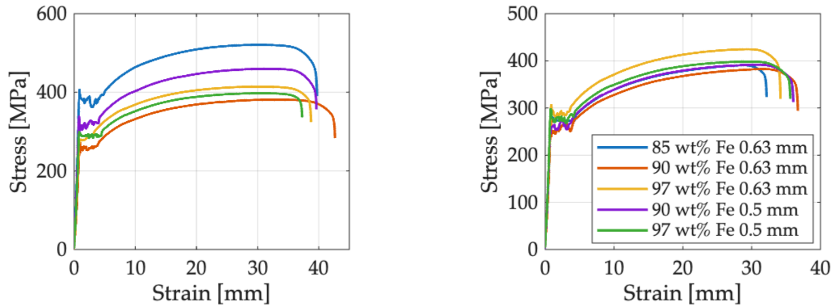


Figure 5: Stress-strain diagram for samples with 85 wt% Fe and a thickness of 0.63 mm.
Source: own.

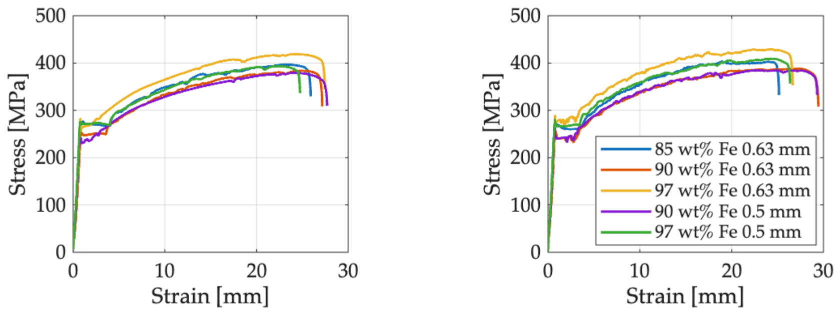
Figure 5 shows the tensile test results for samples with 85% Fe and a thickness of 0.63 mm. The sample tested at 90 °C achieved the highest values of all the measured properties, including elastic modulus, yield strength, tensile strength and elongation. At 110 °C all the properties decreased significantly, with sample 2 showing the lowest tensile strength in this group. At 130 °C and 150 °C, the sample tested at the higher temperature exhibited a lower elastic modulus and yield strength, while the differences in elongation were minor, and tensile strength varied more noticeably. At 170 °C and 190 °C, the sample tested at the lower temperature showed the smallest elongation, whereas the difference in tensile strength was more pronounced. The samples tested at 210 °C, 230 °C, and 250 °C again showed a gradual decline in mechanical properties, with the lowest elastic modulus and yield strength recorded at 230 °C. A slight increase in tensile strength and elongation can be observed at the highest temperatures. Overall, the results indicate a clear decreasing trend in elastic modulus and yield strength with increasing temperature. Figures 6 to 10 present the stress–strain diagrams for all the samples tested at temperatures from 90 °C to 250 °C.



a) b)

Figure 6: Stress-strain diagram at a) 90 °C and b) 110 °C.

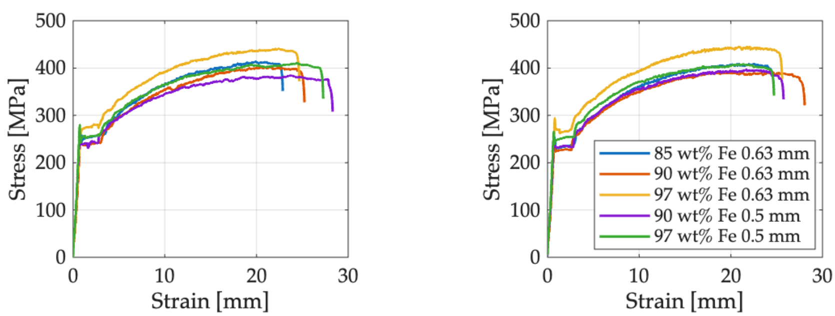
Source: own.



a) b)

Figure 7: Stress-strain diagram at a) 130 °C and b) 150 °C.

Source: own.



a) b)

Figure 8: Stress-strain diagram at a) 170 °C and b) 190 °C.

Source: own.

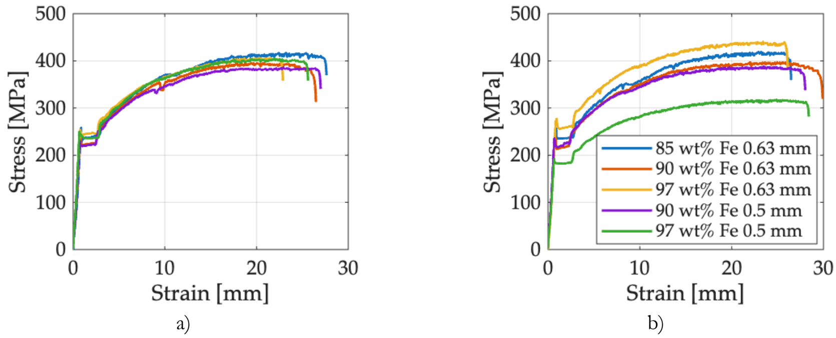


Figure 9: Stress-strain diagram at a) 210 °C and b) 230 °C.
Source: own.

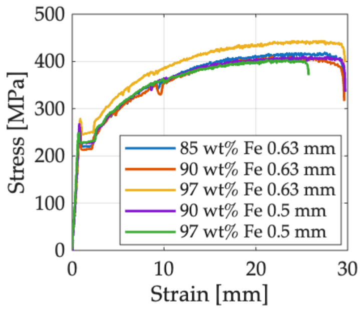


Figure 10: Stress-strain diagram at 250 °C.
Source: own.

The results presented in Figures 6 to 10 demonstrate a consistent and clearly distinguishable influence of chemical composition, particularly the Fe content and the presence of alloying elements, as well as sample thickness, on the material's mechanical response. At all the investigated temperatures, the highest values of upper yield strength and ultimate tensile strength were achieved most frequently by samples containing 97 wt% iron. These samples generally exhibited a stronger and more stable mechanical response, especially those with a thickness of 0.63 mm, which achieved the highest strength values across nearly all the temperature levels. A chemical analysis confirmed that these samples contained very low amounts of Si, P, and Al compared to the others. Since Si and Al affect solid-solution strengthening and P increases strength only in very small amounts, their reduced presence likely contributed to the more favourable mechanical behaviour. In addition, the 97 wt% Fe samples exhibited higher levels of Cu, Cr, Mn, Ni, and Mo, all of which are known to increase strength. Cr and Mo, in particular, improve high-temperature strength significantly, while Mo also enhances creep resistance. The largest elongations were recorded in the samples with 90 wt% iron, regardless of whether their thickness was 0.63 mm or 0.5 mm. The chemical compositions of these samples differed only minimally, with average deviations of approximately 0.04 ± 0.02 wt% in Si, Al, P, Cu, and Cr, and only a few thousandths of a percent in Ni, Mo, Ti, and S. These samples achieved the highest elongation values consistently, but, simultaneously, displayed some of the lowest yield strength and tensile strength values, which is consistent with the expected trade-off between strength and ductility. The lowest elongations were observed in samples with 85 wt% Fe and 0.63 mm thickness, as well as those with 97 wt% Fe and 0.5 mm thickness. These two materials differ significantly in chemical composition, sharing similarity only in their Mn and Ni content, while exhibiting substantial differences in Cu, Cr, S, Ti, Al, and Si. No single dominant factor explains their reduced elongation. The result was likely a combined effect of multiple alloying elements and microstructural interactions, amplified at elevated temperatures.

Across all the temperature ranges, a gradual decrease in yield strength, tensile strength, and elongation was observed with increasing temperature, although the selected samples exhibited local deviations due to their individual chemical compositions. The strength values were highest at 90 °C and generally decreased up to 230 °C. At 250 °C the results became more uniform, with only isolated samples showing significant deviations. The most important conclusion is that chemical composition is the dominant factor governing the mechanical response at elevated temperatures, more so than thickness alone. Samples with 97 wt% Fe and increased levels of Cr, Mo, Ni, Mn, and Cu achieved the highest strength, while samples with 90 wt% Fe exhibited the highest ductility consistently. The combined influence of individual alloying elements, not just Fe content, determines the final mechanical behaviour, and explains why samples with similar iron content can behave differently at the same temperature. Figure 11 shows the diagram of length change d_L as a function of temperature for samples with thicknesses of 0.63 mm and 0.5 mm.

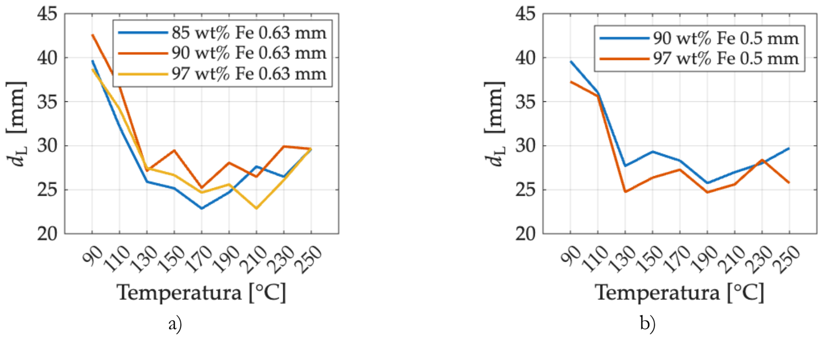


Figure 11: Diagram of length change d_L as a function of temperature for samples with thicknesses of a) 0.63 mm and b) 0.50 mm.
Source: own.

In both cases, the highest elongations were recorded at the lowest test temperature (90 °C), after which elongation decreased consistently with the increasing temperature. Figure 11a shows the elongation of the 0.63 mm samples as a function of temperature. The highest elongations were recorded at 90 °C, ranging from 39.7 mm to 42.7 mm, after which elongation decreased steadily with the increasing temperature and stabilised between 22 mm and 30 mm. The samples containing 90 wt% Fe achieved the highest elongations across most temperatures, whereas the 85 wt% Fe samples exhibited the lowest values consistently. These differences correspond to the chemical composition: the 85 wt% Fe samples contained significantly higher P levels, which increase strength but reduce ductility. In contrast, the 90 wt% Fe samples contained more Al, which improves toughness, as well as lower Mn levels, reducing the risk of ductility loss. Small additions of Ti supported the favourable behaviour of this group further.

A similar trend was observed for the 0.50 mm samples. Figure 11b presents the elongation results for the 0.50 mm samples. As with the thicker samples, the highest elongations were obtained at 90 °C, followed by a pronounced drop between 90 °C and 130 °C. At higher temperatures, the elongation stabilised within 25–30 mm. Samples with 90 wt% Fe again achieved the highest elongations throughout the temperature range, influenced strongly by their elevated Si, Al, and P contents. The 97 wt% Fe samples showed slightly higher Cr and Ni levels, which increase strength and therefore limit elongation. Overall, the samples with higher Si contents achieved greater elongation, because Si strengthens ferrite without reducing ductility significantly, whereas an elevated P content had the opposite effect. Figure 12 shows the diagram of upper yield strength R_{eH} as a function of temperature for samples with thicknesses of 0.63 mm and 0.5 mm.

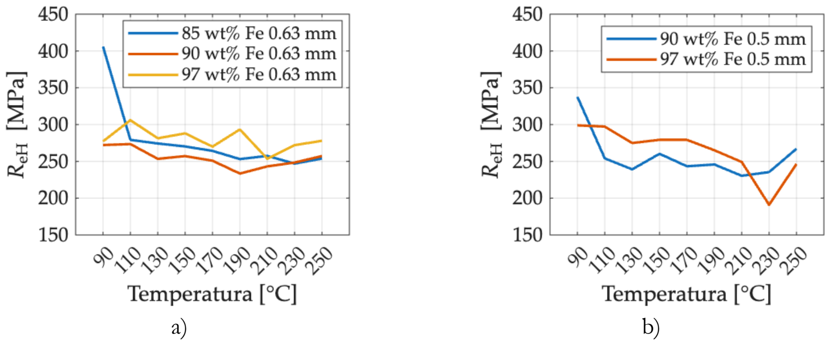


Figure 12: Diagram of upper yield strength R_{eH} as a function of temperature for samples with thicknesses of a) 0.63 mm and b) 0.50 mm

Source: own.

Figure 12a shows the upper yield strength of the 0.63 mm samples as a function of temperature. The results indicate that samples containing 97 wt% Fe achieved the highest yield strength values consistently. At 90 °C, the differences between the samples were more pronounced, while, at higher temperatures, the values converged gradually and remained within 230–305 MPa. A general downward trend of yield strength with increasing temperature was evident. The chemical analysis helps explain these trends. The 97 wt% Fe samples contained the lowest amounts of Si and P, elements known to reduce ductility and toughness when present in higher concentrations. These samples also showed slightly elevated Mo contents, which is consistent with their improved high-temperature strength. The samples with 90 wt% Fe reached the lowest yield strength values across the full temperature range. Their results were comparable to those of the 85 wt% Fe group, which is consistent with their similar levels of Cu, Cr, Mn, Mo and S.

Figure 12b presents the results for the 0.50 mm samples. As observed for the thicker group, samples with 97 wt% Fe generally achieved the highest yield strength values. More noticeable deviations occurred at 90 °C and 230 °C, where the 90 wt% Fe sample reached slightly higher values than expected. Across all the samples a clear decline in yield strength was observed as the temperature increases. The elevated values of the 97 wt% Fe samples correlated with their higher contents of Cu, Cr, Ni, and Mo, elements known to enhance strength and hardness. These samples also contained significantly less S, which, typically, appears as sulphide inclusions and affects ductility adversely. In contrast, the 90 wt% Fe samples exhibited two- to three-fold higher Si and elevated P levels, both of which can increase strength, but reduce ductility when present in excessive amounts. Figure 13 shows the diagram of maximum tensile strength R_m as a function of temperature for samples with thicknesses of 0.63 mm and 0.5 mm.

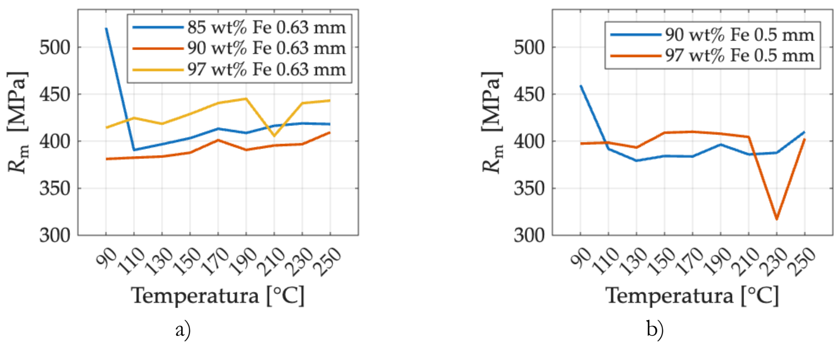


Figure 13: Diagram of maximum tensile strength R_m as a function of temperature for samples with thicknesses of a) 0.63 mm and b) 0.50 mm

Source: own.

Figure 13a shows the tensile strength of samples with a thickness of 0.63 mm at different testing temperatures. On average, the samples containing 97 wt% Fe achieved the highest tensile strength. A notable deviation occurred only at 90 °C, where the 85 wt% Fe samples reached 520 MPa. With increasing temperature, the results stabilised between 380 MPa and 450 MPa, and the overall average tensile strength for this thickness was approximately 414 MPa. The chemical analysis revealed that the 97 wt% Fe samples contained the lowest concentrations of Si and P. Since P can reduce ductility and toughness significantly when present in larger amounts, its low content is consistent with the higher observed tensile strength. These samples contained practically no Al, but showed slightly elevated Mo levels, which are known to enhance tensile strength at elevated temperatures. The 90 wt% Fe samples exhibited the lowest tensile strength consistently across the entire temperature range, with values comparable to those of the 85 wt% Fe group. Their chemical composition showed similar contents of Cu, Cr, Mn, Mo, and S. A slightly higher Ti content was observed in the 85 wt% Fe group, which generally increases strength and hardness. More pronounced differences were found in Si, Al, and P, all present in higher concentrations in the 90 wt% Fe samples.

Figure 13b shows the tensile strength of samples with a thickness of 0.5 mm. As before, the 97 wt% Fe samples achieved the highest values in most tests, except at 90 °C, where the 90 wt% Fe sample reached 460 MPa. A more noticeable drop occurred for the 97 wt% Fe sample at 230 °C. Compared to the 0.63 mm group, the reduction in tensile strength with increasing temperature was less pronounced. The higher strength of the 97 wt% Fe samples is supported by their increased contents of Cu, Cr, Ni, and Mo. These alloying elements enhance hardness and tensile strength significantly. This group also contained substantially less S, which, typically, appears as sulphide inclusions, and can influence mechanical performance negatively. The Mn and Ti contents were similar between the chemical groups, while the Si levels in the 90 wt% Fe samples were two to three times higher. Al was not detected in the 97 wt% Fe samples.

5 Conclusion

This paper examined the mechanical behaviour of steel with varying iron contents and alloying compositions at elevated temperatures. The combined evaluation of chemical composition and high-temperature tensile testing showed that temperature and alloying chemistry determine the material's strength and ductility jointly. Samples containing 97 wt% Fe achieved the highest yield strength and tensile strength consistently across most temperatures. Their favourable behaviour is linked to the low contents of Si, P, and Al and slightly higher amounts of Cr, Mo, Ni, Mn, and Cu, all of which improve high-temperature strength. In contrast, the samples with 90 wt% Fe exhibited the highest ductility, due primarily to their higher Si and Al contents and lower Mn levels. The lowest elongations were observed in the 85 wt% Fe samples and in the thinner 97 wt% Fe samples, reflecting the combined influence of multiple alloying elements rather than a single dominant factor.

Temperature had a clear and consistent effect: the yield strength, tensile strength, and elongation decreased with the increasing temperature, with the greatest differences observed at 90 °C, and progressively smaller differences observed as the temperature increased toward 250 °C. At higher temperatures, the mechanical response became more uniform, regardless of thickness. Overall, the results indicate that the chemical composition is the primary factor governing mechanical behaviour at elevated temperatures, while sample thickness plays a secondary role. These findings provide a useful basis for selecting steel grades for thermally demanding applications, where the balance between strength and ductility depends on the combined effects of specific alloying elements.

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Povzetek v slovenskem jeziku

Analiza mehanskih lastnosti jekla pri povišanih temperatura. Članek predstavlja vpliv povišanih temperatur na mehanske lastnosti jekla z različno vsebnostjo železa in legirnimi dodatki. V raziskavi so združeni kemijska analiza in natezni preizkusi pri povišanih temperaturah z namenom preučitve vpliva mikrostrukture, kemijske sestave in temperature na mejo tečenja, natezno trdnost in duktilnost jekla. Analizirani in razvrščeni so bili vzorci dveh debelin (0,63 mm in 0,50 mm) ter treh vsebnosti železa (85 mas. %, 90 mas. % in 97 mas. %), glede na njihovo kemijsko sestavo. Natezni preizkusi so bili izvedeni v skladu s standardom ISO 6892-2 v temperaturnem območju od 90 °C do 250 °C, v korakih po 20 °C. Rezultati poudarjajo skupni vpliv temperature in legirne kemije na obnašanje jekla pri povišanih temperaturah ter zagotavljajo dragocene usmeritve za izbiro materialov v termično zahtevnih inženirskih aplikacijah.