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SHOT TEMPERING

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Deliverable D2.2: Metallurgical information of the considered steels

ShotTempering

Shot Peening Integration in Tempering Processes of Steels
for Enhanced Fatigue Performance

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Project Abstract

In response to pressing challenges, such as climate change and the increasing need for enhanced energy efficiency in the transport sector, the ShotTempering project addresses the imperative for advancements in the production process chain. This project introduces an innovative hybrid technique known as "warm peening," which integrates shot peening within the tempering treatment of components, primarily for high-demand applications like electric vehicles (EVs). EVs impose substantially higher loads on their components, necessitating further refinements in the production process to enhance performance and prevent premature failures. The novel warm peening process offers dual advantages. Firstly, it promises to boost the overall efficiency of the process chain in terms of energy consumption, resource utilization, and time savings. Secondly, it holds the potential to significantly enhance the mechanical properties of manufactured parts, particularly their fatigue resistance, through shot peening at elevated temperatures. This technique is recognized for its capacity to augment cyclic residual stress stability, fatigue strength, and, consequently, the longevity of critical components. The ShotTempering project represents a pioneering endeavour poised to revolutionize the manufacturing landscape, catering to the evolving demands of the transport sector while contributing to sustainability and energy efficiency goals.

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Public Summary

Deliverable 2.2 presents the metallurgical characterization of the three steel grades selected for the ShotTempering project, each corresponding to a different heat treatment and processing route.

- Route 1 – 27MnCr5: case hardening.
- Route 2 – 42CrMo4: conventional hardening (quenching and tempering).
- Route 3 – C55: surface induction hardening.

The characterization campaign included chemical composition analysis, microstructural evaluation, hardness profiling, and mechanical testing after tempering at different temperatures.

The tempering temperatures evaluated were specifically selected to match the working range expected for warm peening operations. Therefore, the results provided in this deliverable establish a solid foundation for selecting optimal heat treatment parameters and understanding the initial properties of the materials prior to further processing in the project.

1 Introduction

1.1 Rationale of this deliverable

Deliverable 2.2 presents a comprehensive metallurgical characterization of the steels selected for the project, as defined in Technical Annex 1 of the Grant Agreement. The analysis includes chemical composition, microstructural evaluation, hardness distribution, and mechanical properties such as tensile and impact resistance, at different tempering temperatures.

As part of WP2, which focuses on steel manufacturing and characterization, the work described in this deliverable is crucial for establishing the baseline properties of the three selected steel grades before further processing and application in demonstrators. The data obtained will serve as a reference for next work packages, ensuring an informed approach to the material's industrial implementation.

The document is structured into three main chapters, each dedicated to one of the selected steel grades: 27MnCr5, 42CrMo4 and C55 (Deliverable 2.1). In each chapter, the metallurgical characterization of the corresponding material is detailed, following the same methodology for consistency. Given that each steel grade has been specifically selected to meet the requirements of a distinct processing route (carburizing, conventional quenching and tempering and surface induction hardening), the characterization results aim to define the baseline metallurgical properties relevant to its intended application, rather than to draw direct comparisons between the materials.

The characterization methodology applied was consistent across the three steel grades, following the same standards and procedures. Since the process was identical for each material, it will only be described in detail in the first section to avoid repetition. This approach ensures uniformity in testing while maintaining full compliance with the established protocols throughout all assessments.

By providing a detailed metallurgical profile of the selected steels, this deliverable contributes essential insights that will support the next phases of experimental validation and process optimization within the project.

<u>Attainment of the objectives and explanation of deviations</u>

All task objectives have been successfully met, with the characterization of the selected steels completed according to the defined methodology. However, the submission of this deliverable was slightly delayed due to the need to subcontract tensile testing. This was necessary as some specimens exhibited higher than expected hardness, a result of the lower tempering temperatures studied, which exceeded the capacity of the available in-house testing equipment.

2 Route 1 – Steel for case hardening – 27MnCr5

2.1 Supplying conditions

27MnCr5 was provided in an isothermally annealed condition, as detailed in the previous deliverable, to refine and homogenize its microstructure for optimal processing.

2.1.1 Chemical composition

The chemical composition was determined using spectroscopy. The analyses were carried out on samples cut from the rolled bars. These samples were prepared following the indications of the standard ISO 14284 [1].

The following table presents the content of most relevant elements in 27MnCr5 steel grade.

Table 1: Chemical composition in weight % of the 27MnCr5 steel.

Steel	C	Mn	Si	S	Cr	Mo
27MnCr5	0,3	1,24	0,29	0,023	1,09	0,24

2.1.2 Microstructural evaluation

Microstructural characterization was performed along the entire section of the bar, analysing three specific regions: surface, mid-radius, and centre. This assessment aimed to verify the homogeneity of the microstructure achieved after the applied isothermal annealing.

Samples were extracted from the flat bar and prepared following the guidelines of ISO 377:20170 “Steel and steel products – Location and preparation of samples and test pieces for mechanical testing” [2]. The specimens were polished and etched with a 3% nital solution to reveal the microstructural features. The analysis was conducted using a 3D optodigital microscope, providing high-definition imaging for a detailed evaluation of phase distribution.

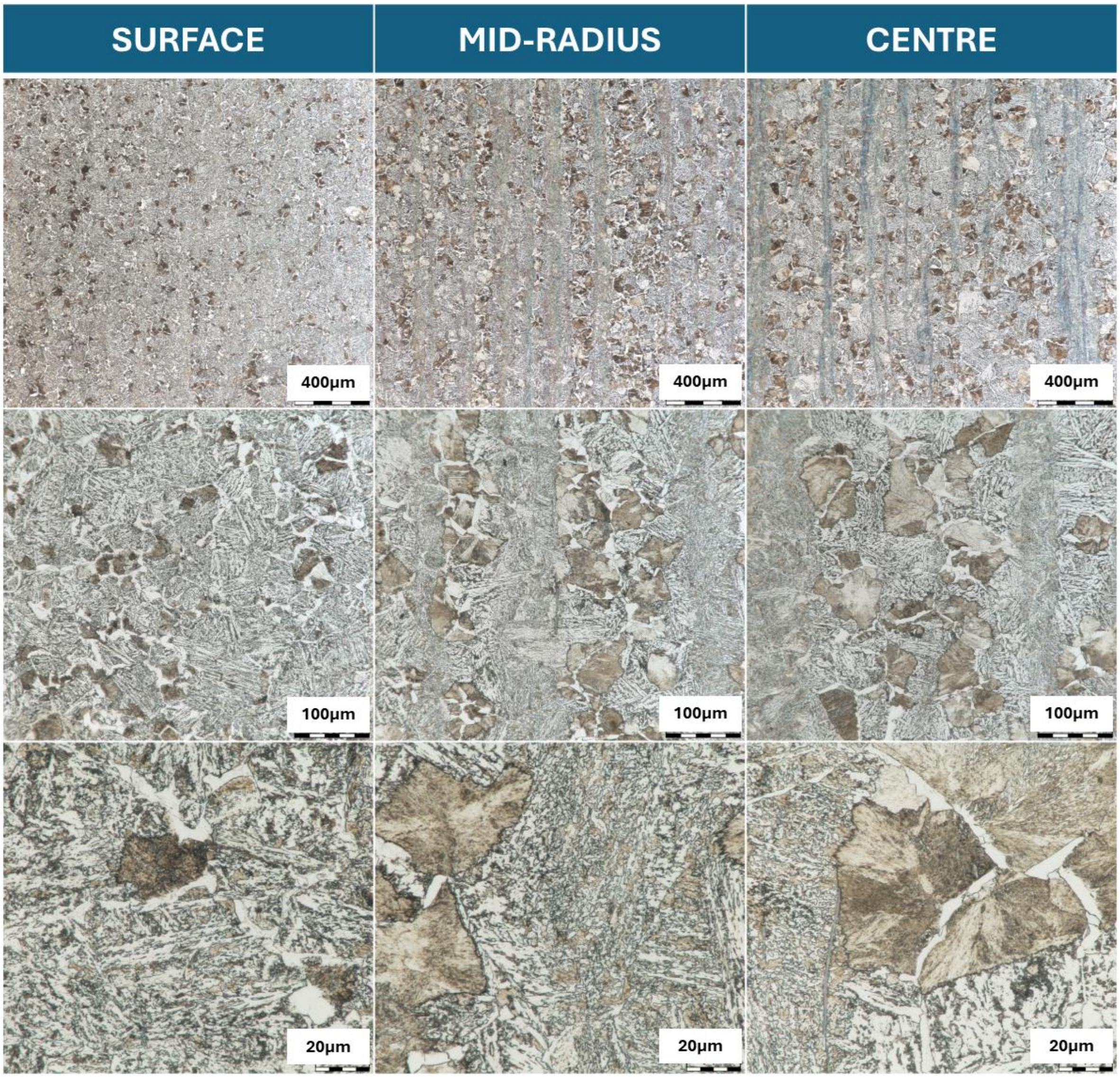

Figure 1: Microstructures obtained at the bar surface (left), mid-radius (middle) and centre (right) for 27MnCr5 steel, bar Ø 70 mm in as rolled conditions.

As can be seen in Figure 1, the as-rolled microstructure is primarily bainitic, with increasing amounts of pearlite and ferrite as the distance from the surface increases. This gradient in microstructural phases is a result of the thermal and mechanical conditions experienced during rolling. Following the isothermal annealing treatment, the microstructure is fully transformed into a homogeneous ferrite-pearlite distribution along the entire section of the bar, ensuring uniform properties throughout the material (Figure 2).

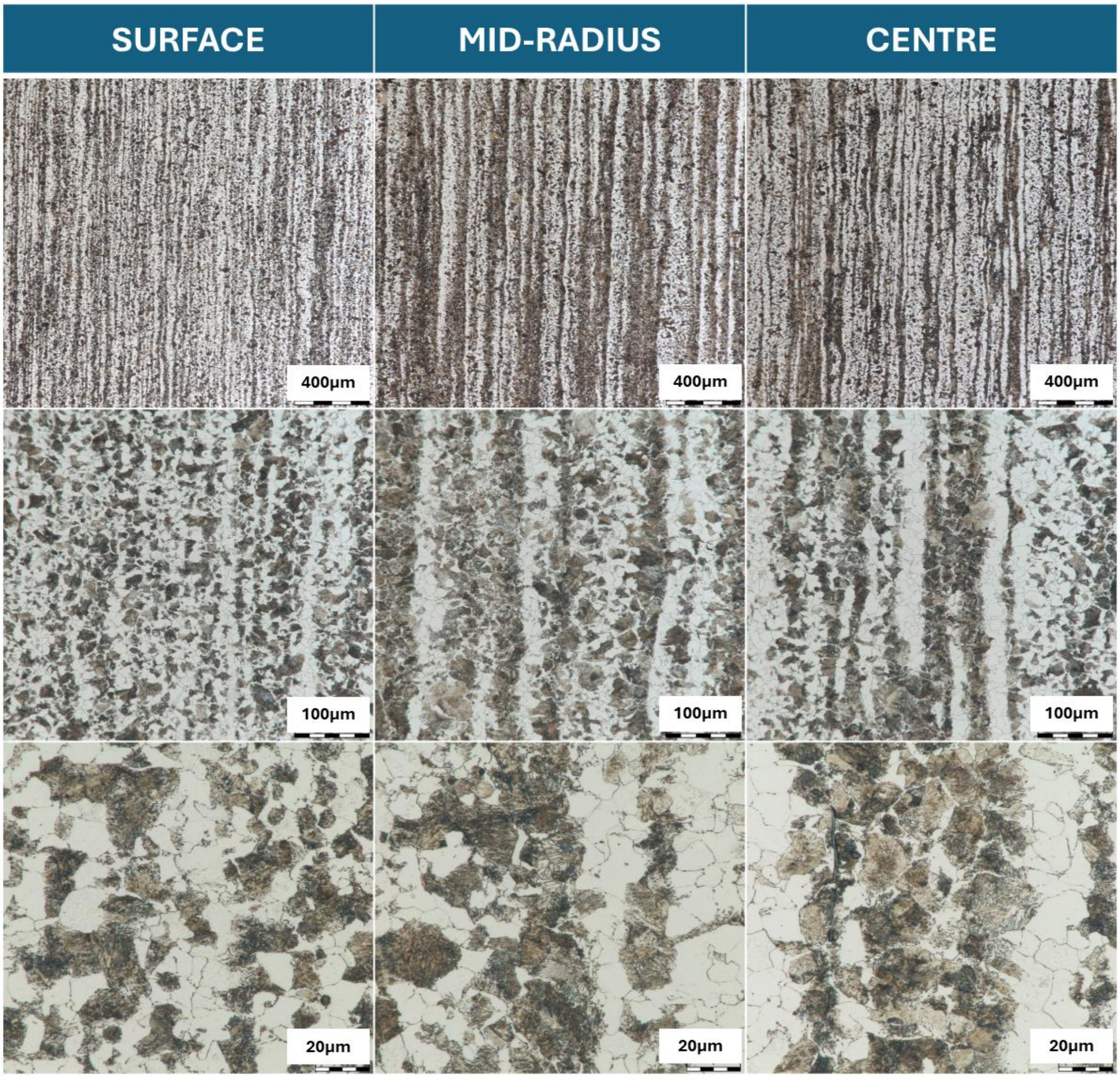

Figure 2: Microstructures obtained at the bar surface (left), mid-radius (middle) and centre (right) for 27MnCr5 steel, bar Ø 70 mm in an isothermally annealed condition.

2.1.3 Determination of the hardness profiles

Hardness measurements carried out during this Task, were conducted following the standard ISO 6507-1:2023 "Metallic materials – Vickers hardness – Part 1: Test method" [3]. One Vickers indentation was performed each mm from the bar surface with a load of 10 kg. Representing the hardness values obtained versus the distance to the bar surface where each indentation was carried out, the hardness profile is obtained.

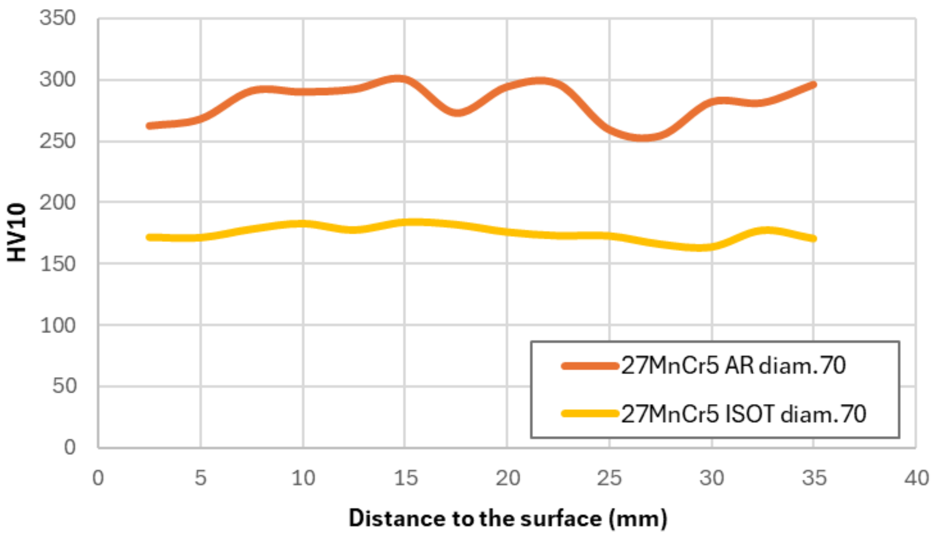

Figure 3: Hardness profiles obtained for 27MnCr5 steel – Route 1 in as rolled conditions (AR) and in an isothermally annealed condition (ISOT).

The microstructural homogeneity after the heat treatment described in the previous section was confirmed by the fact that the obtained hardness profile remained relatively uniform across the bar section. Additionally, a noticeable drop in hardness was observed after the heat treatment, corresponding to the transformation from the harder bainitic structure in the as-rolled condition to the softer ferrite-pearlite microstructure.

2.2 Tempering curves

To assess the fundamental effects of tempering on the mechanical properties of the selected steels, previously quenched specimens were tempered at seven different temperatures, ranging from 200°C to 500°C in 50°C increments. These temperatures were chosen within the range relevant to the warm peening process. The objective of this evaluation was to analyse the evolution of tensile and impact properties as a function of tempering temperature, providing key insights into the steel mechanical behaviour and its response to different heat treatment conditions.

The testing procedure involved several sequential steps: first, specimens were machined transversely to the rolling direction from the steel bars (Figure 4). These specimens were austenitized in a heat treatment furnace at 850°C for 60 minutes and oil quenched. A stress-relief treatment was then applied at 200°C for 120 minutes to reduce residual stresses and prevent cracking between quenching and the different tempering processes. Finally, tempering was carried out at different temperatures, with three specimens treated at each temperature to ensure results repeatability. After heat treatment, mechanical tests were performed on the tempered specimens.

Figure 4: Machined specimens for tensile and impact tests.

2.2.1 Hardness and toughness tests

Hardness measurements were performed in accordance with ISO 6507-1:2023 [3], as described in the previous section. A complete hardness profile was measured from the surface to the centre of the bar. However, due to the minimal variation in hardness values throughout the section, only the average hardness for each tempering temperature is presented in the results. This uniformity is a result of the quenching and tempering process, which ensures a homogeneous hardness distribution from surface to core.

Steel toughness was evaluated through the Charpy impact test, in which a pendulum of known mass and length is dropped from a known height to impact a notched specimen. Absorbed energy is determined by measuring the difference in hammer height before and after the fracture (KCV). The test was conducted following the standard ISO 148-1:2016 "Metallic materials – Charpy pendulum impact tests – Part 1: Test method" [4]. V-notched specimens were machined for testing, and three repetitions were conducted for each test condition at room temperature.

Results of the hardness and toughness tests are presented in Figure 5.

2.2.2 Tensile tests

This test consists in applying a tensile load on the specimen until fracture takes place. Measuring different parameters such as the applied load or the strain, some important mechanical properties of the steel, such as UTS, YS, RoA or El, are determined. Besides, the true stress-strain curve is also obtained.

All the experiments were carried out according to the standard ISO 6892-1:2019 "Metallic materials - Tensile testing - Part 1: Method of test at room temperature" [5]. Three repetitions of each test case were performed.

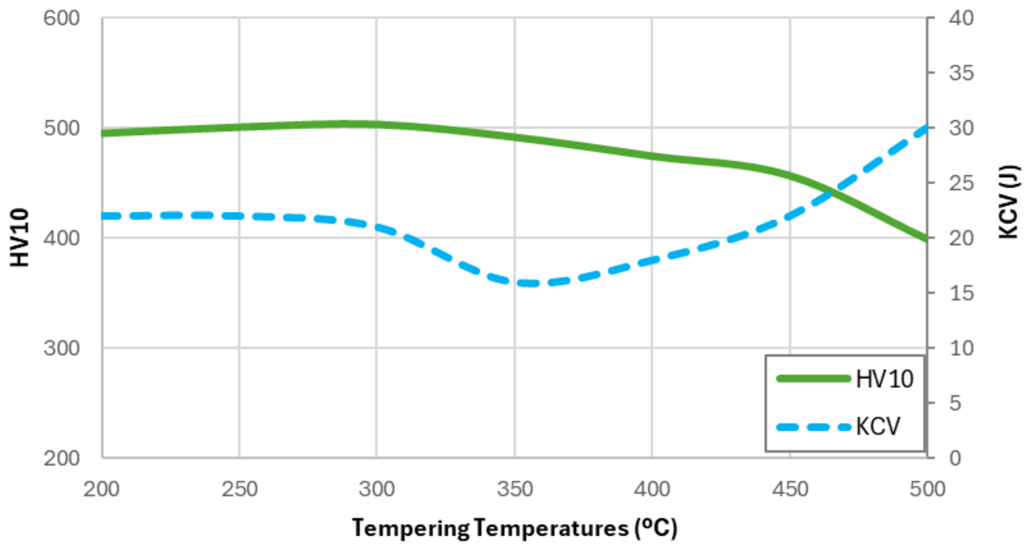

Figure 5: Hardness and toughness results for 27MnCr5 at different tempering temperatures.

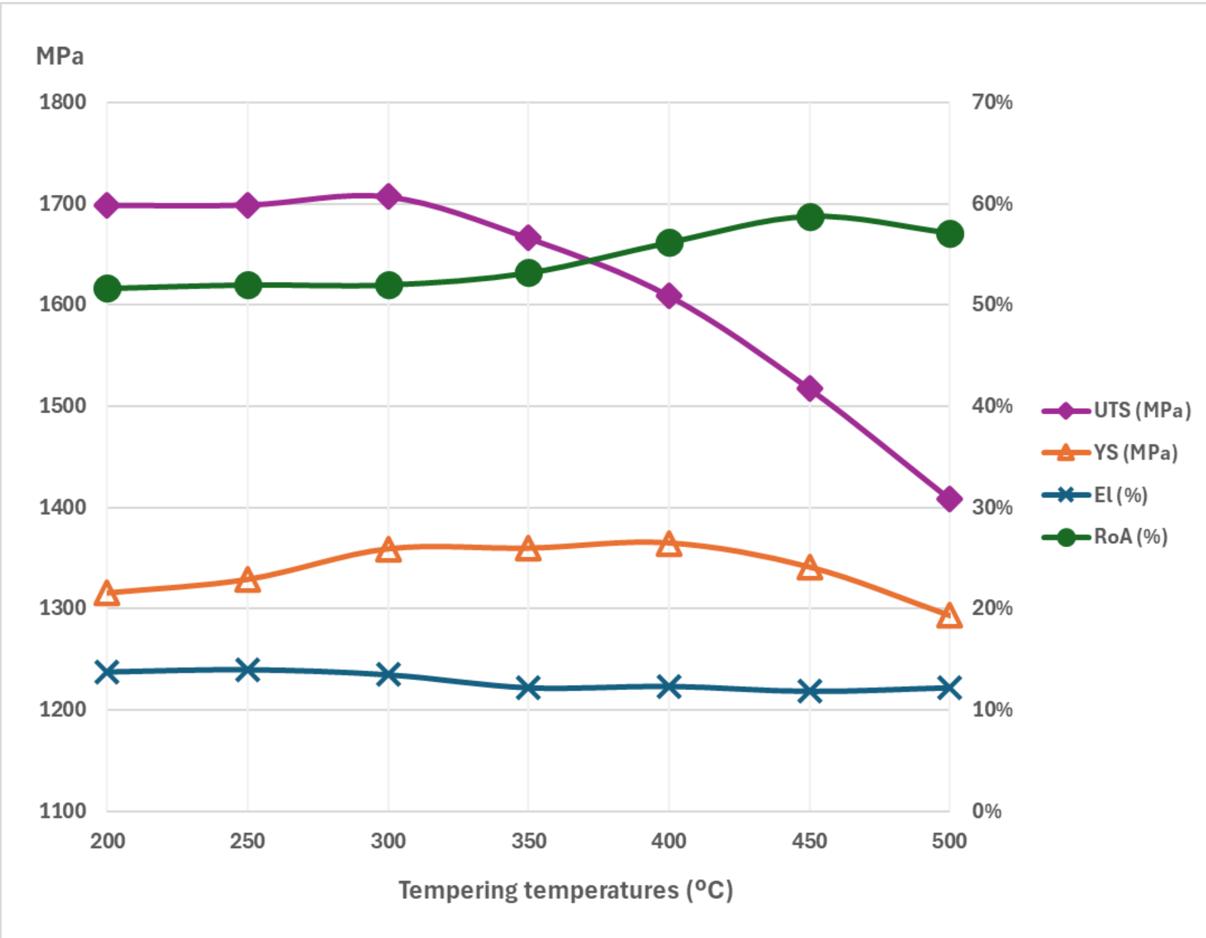

Figure 6: Tensile results for 27MnCr5 at different tempering temperatures.

2.2.3 Microstructural evaluation

As expected, based on the applied heat treatment (austenitization, quenching and tempering) resulting microstructure in all tempered specimens corresponds to tempered martensite. This microstructural state is characteristic of steels subjected to such thermal cycles, where the rapid cooling from the austenitization temperature promotes martensitic transformation, and the following tempering step stabilizes the structure by relieving internal stresses and enabling the precipitation of carbides. The presence of tempered martensite across all temperatures confirms the effectiveness of the heat treatment applied throughout the tempering study.

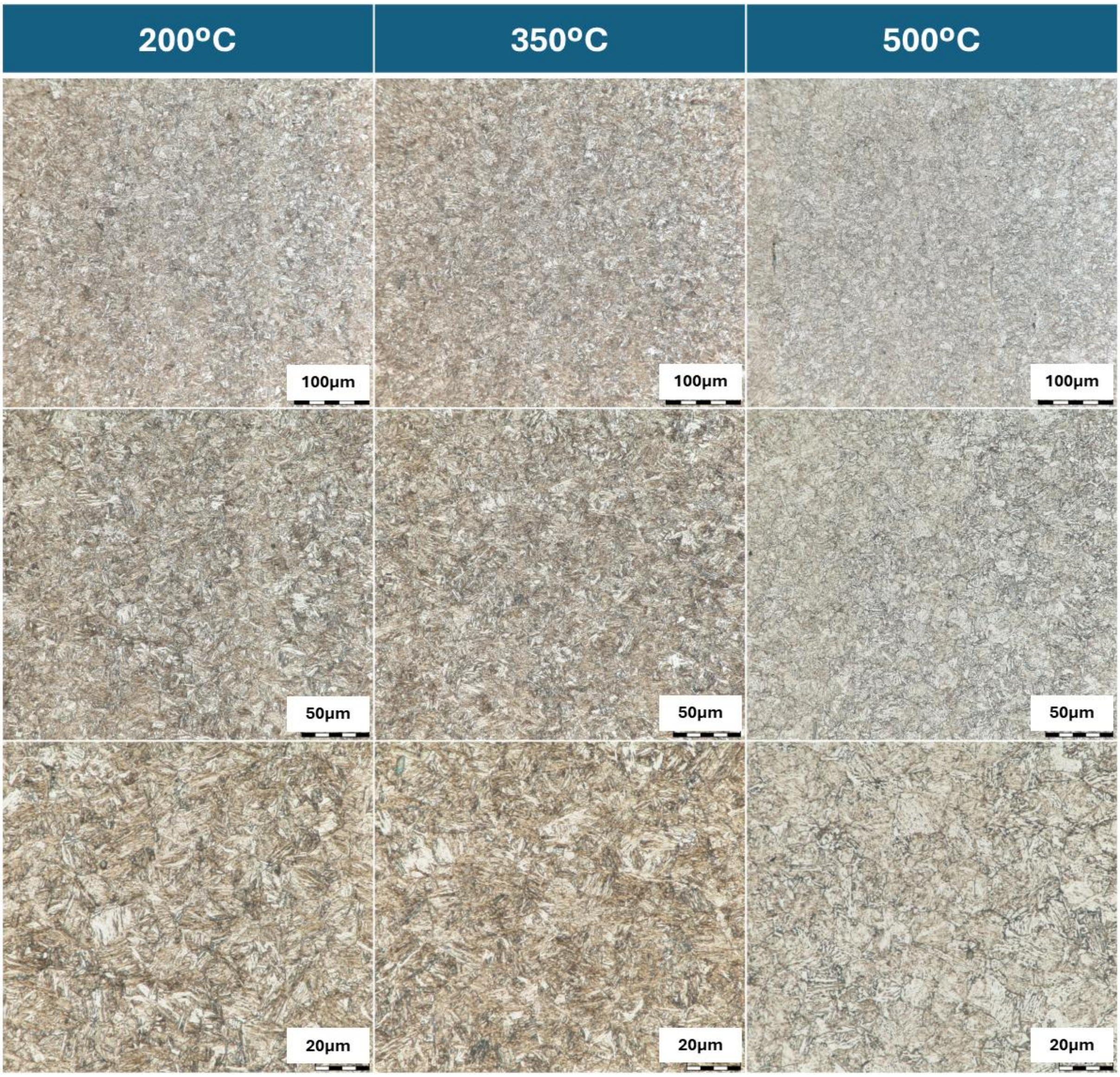

Figure 7: Examples of microstructures obtained at tempering temperatures of 250ºC (left), 350ºC (middle) and 500ºC (right) for 27MnCr5 steel.

3 Route 2 – Conventional hardening – 42CrMo4

3.1 Supplying conditions

42CrMo4 steel grade was supplied in as rolled conditions as described in Deliverable 2.1.

Initial characterization of this steel was conducted under the supplied conditions, as this represents the material's original state upon arrival in an industrial environment, ready for its first machining operation. This method is essential for evaluating the steel's properties in its most representative form, before any additional treatments or transformations. This provides a robust reference for the steel's behaviour under standard operating conditions, serving as a foundation for future assessments and process optimizations throughout the manufacturing route.

3.1.1 Chemical composition

The following table presents the chemical composition of the steel selected for Route 2.

Table 2: Chemical composition in weight % of the 42CrMo4 steel.

Steel	C	Mn	Si	S	Cr	Mo
42CrMo4	0,44	0,87	0,29	0,025	1,1	0,03

3.1.2 Microstructural evaluation

Microstructural evaluation showed no significant differences between surface and centre of the bar. Initial microstructure in the supplied condition is predominantly bainitic through the entire section as can be seen in Figure 8.

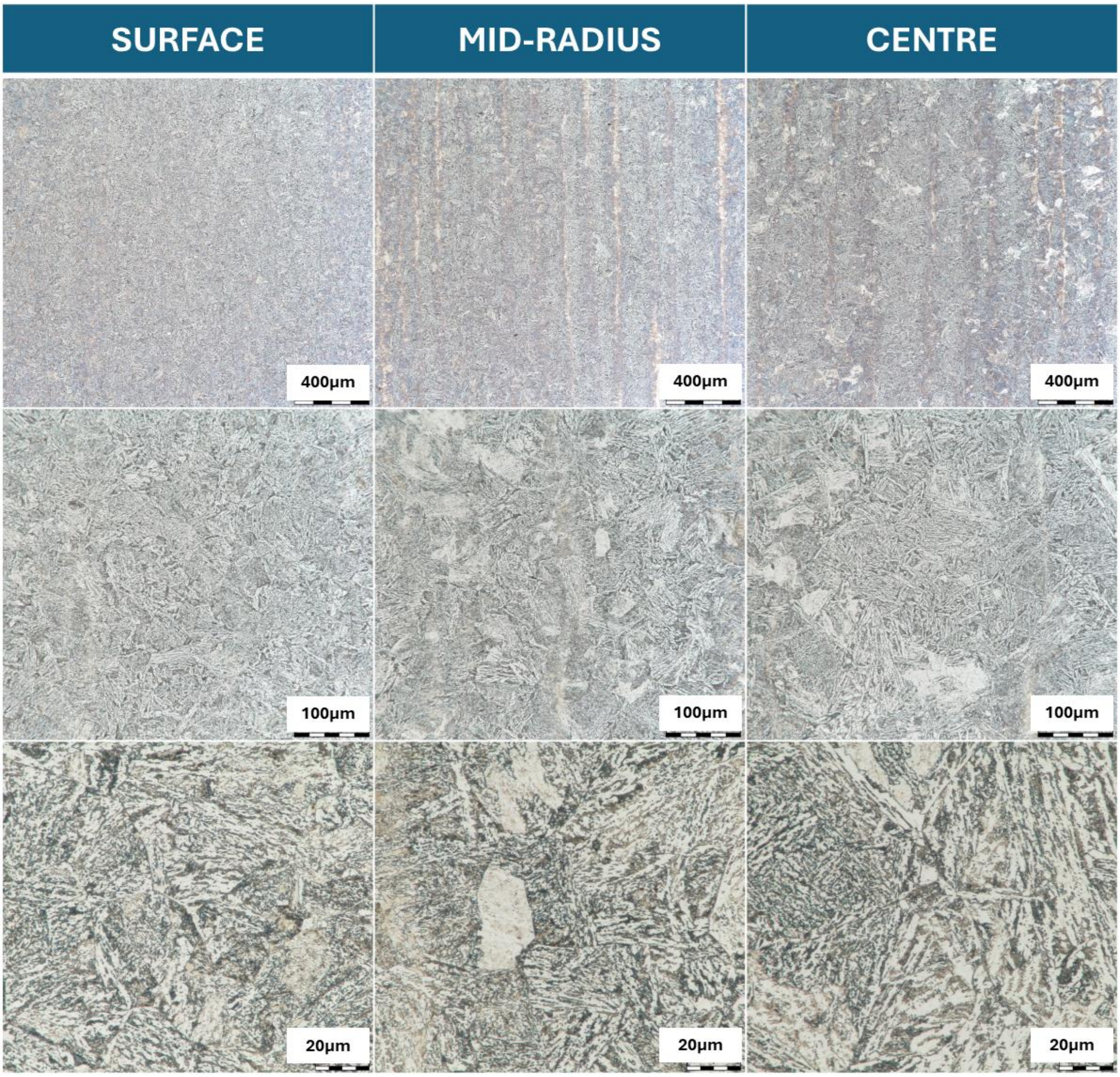

Figure 8: Microstructures obtained at the bar surface (left), mid-radius (middle) and centre (right) for 42CrMo4 steel, bar Ø 60 mm in as rolled condition.

3.1.3 Determination of the hardness profiles

The hardness profile further confirms the previously mentioned microstructural homogeneity, as it exhibits a relatively flat distribution through the section.

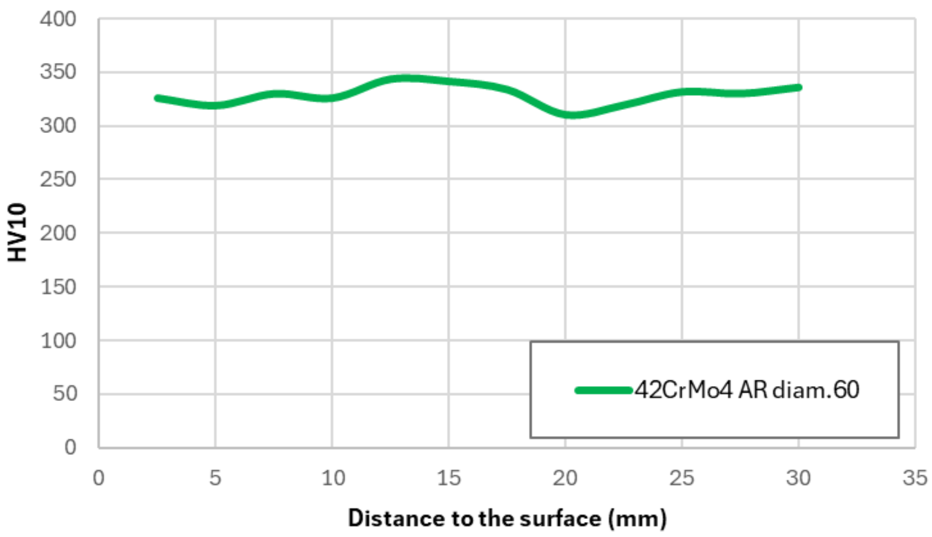

Figure 9: Hardness profile obtained for 42CrMo4 steel – Route 2 in as rolled conditions (AR).

3.2 Tempering curves

The heat treatment applied for these tempering curves is the same as that described in Section 2.1 for Route 1. Analysed tempering temperatures were also the same: 200°C, 250°C, 300°C, 350°C, 400°C, 450°C, and 500°C.

3.2.1 Hardness and toughness tests

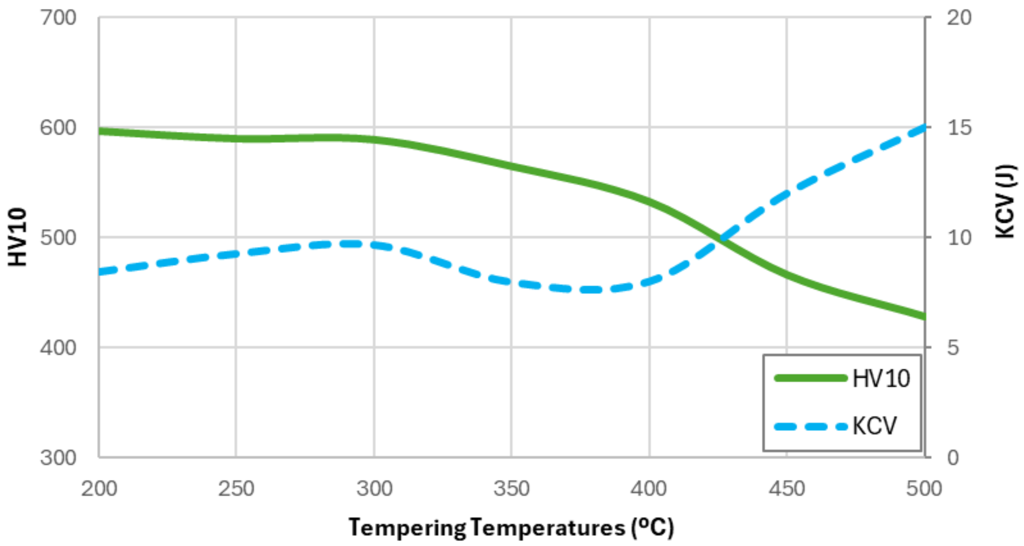

Figure 10: Hardness and toughness results for 42CrMo4 at different tempering temperatures.

3.2.2 Tensile tests

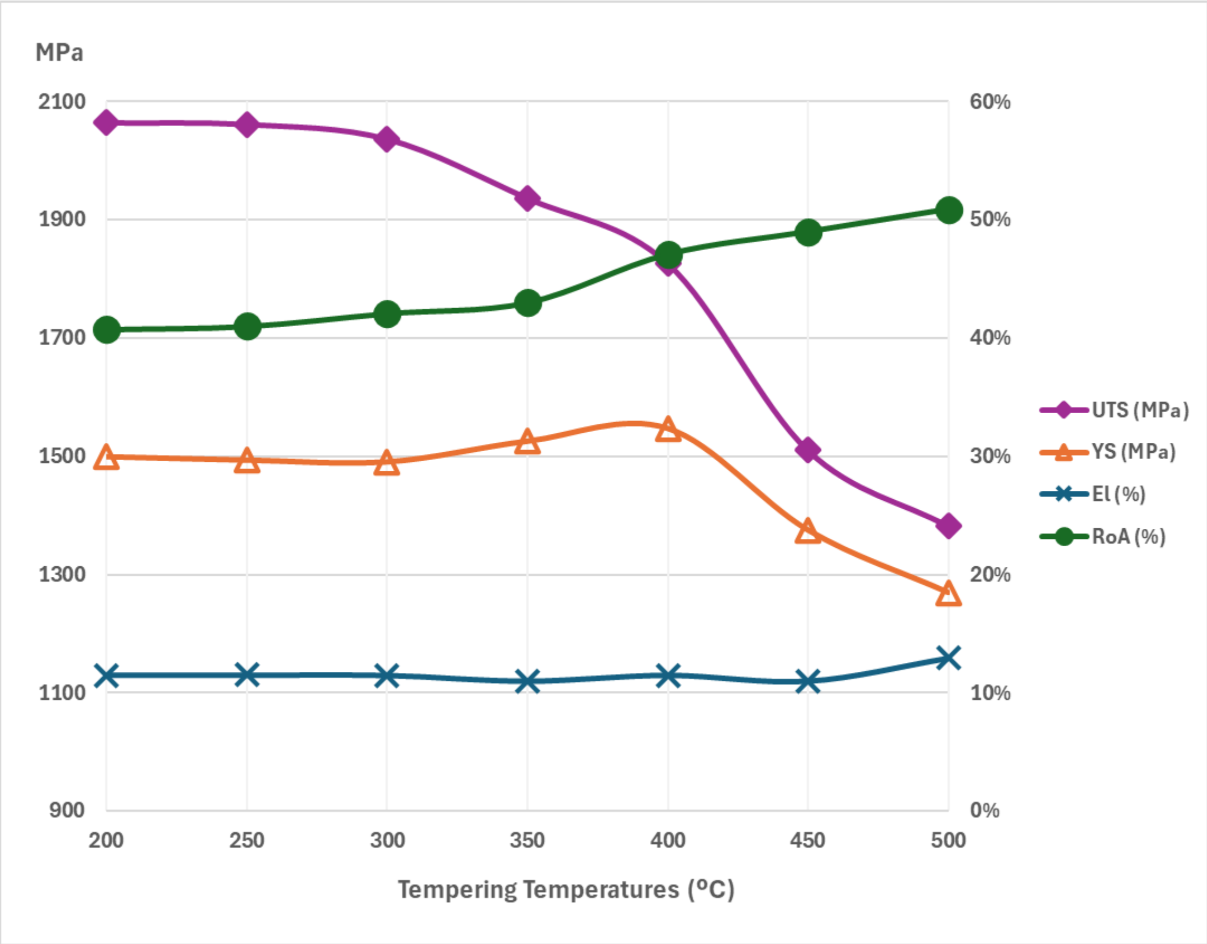

Figure 11: Tensile results for 42CrMo4 at different tempering temperatures.

3.2.3 Microstructural evaluation

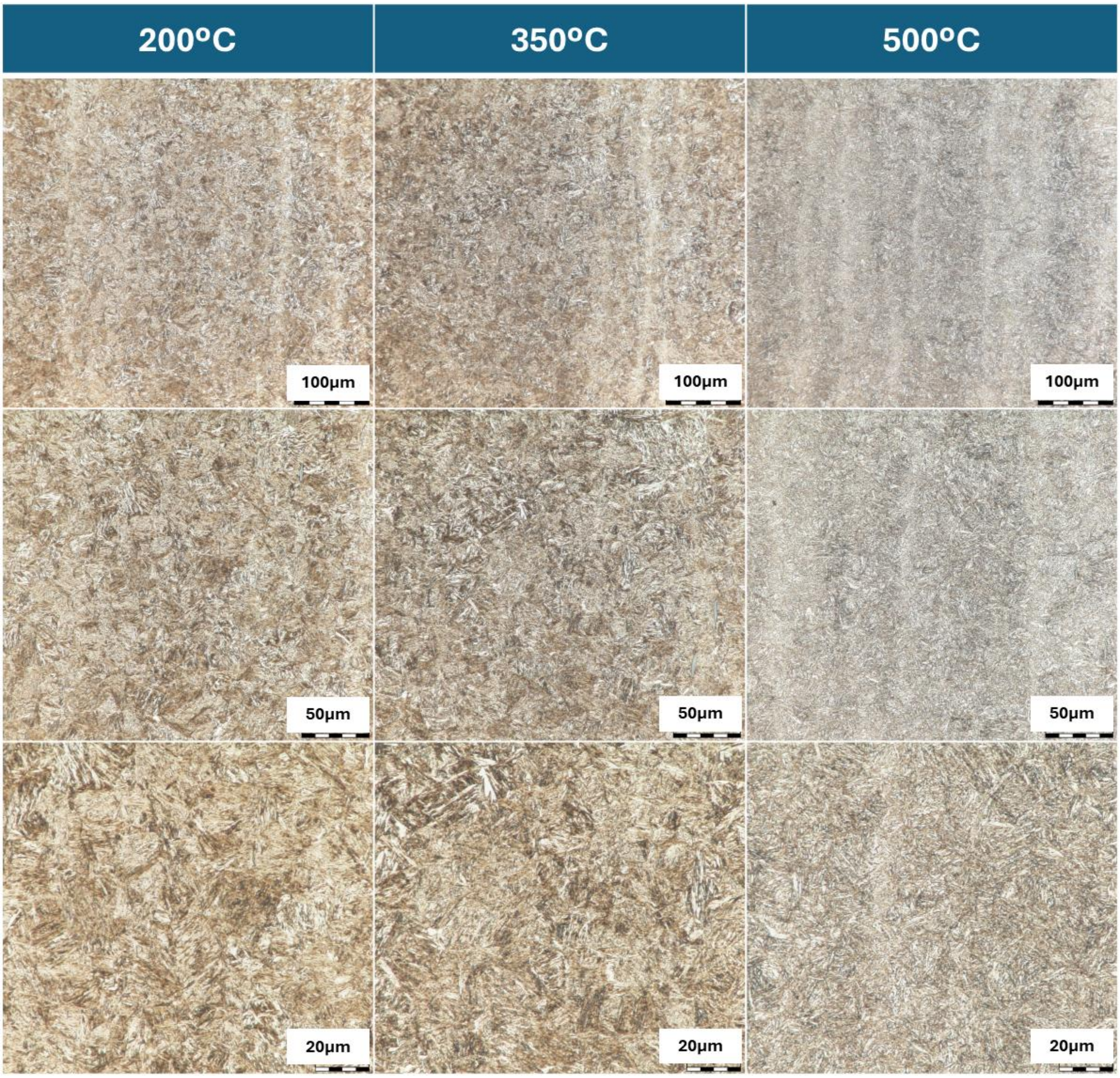

Figure 12: Examples of microstructures obtained at tempering temperatures of 250ºC (left), 350ºC (middle) and 500ºC (right) for 42CrMo4 steel.

4 Route 3 – Surface induction hardening – C55

4.1 Supplying conditions

Steel for Route 3, C55, was supplied in as rolled condition and its initial characterization was conducted in the supplied state, following the same approach as for the steel in Route 2. As explained in the previous section, this ensures that the evaluation accurately reflects the material's properties in its delivered state, just as it would be received in an industrial setting before any further processing.

4.1.1 Chemical composition

Chemical composition of C55 steel is presented in Table 3.

Table 3: Chemical composition in weight % of the C55 steel.

Steel	C	Mn	Si	S	Cr	Mo
C55	0,57	0,73	0,29	0,013	0,21	0,03

4.1.2 Microstructural evaluation

The microstructure resulting from the hot rolling process consists of a ferrite-pearlite mixture uniformly distributed along the entire section of the bar. However, a variation in grain size was observed, with coarser grains present in the core compared to the surface regions. This difference is attributed to the slower cooling rate experienced at the centre of the bar during processing, which allows for grain growth. Despite this gradient in grain size, the overall phase distribution remains constant, confirming a stable ferrite-pearlite structure throughout the section

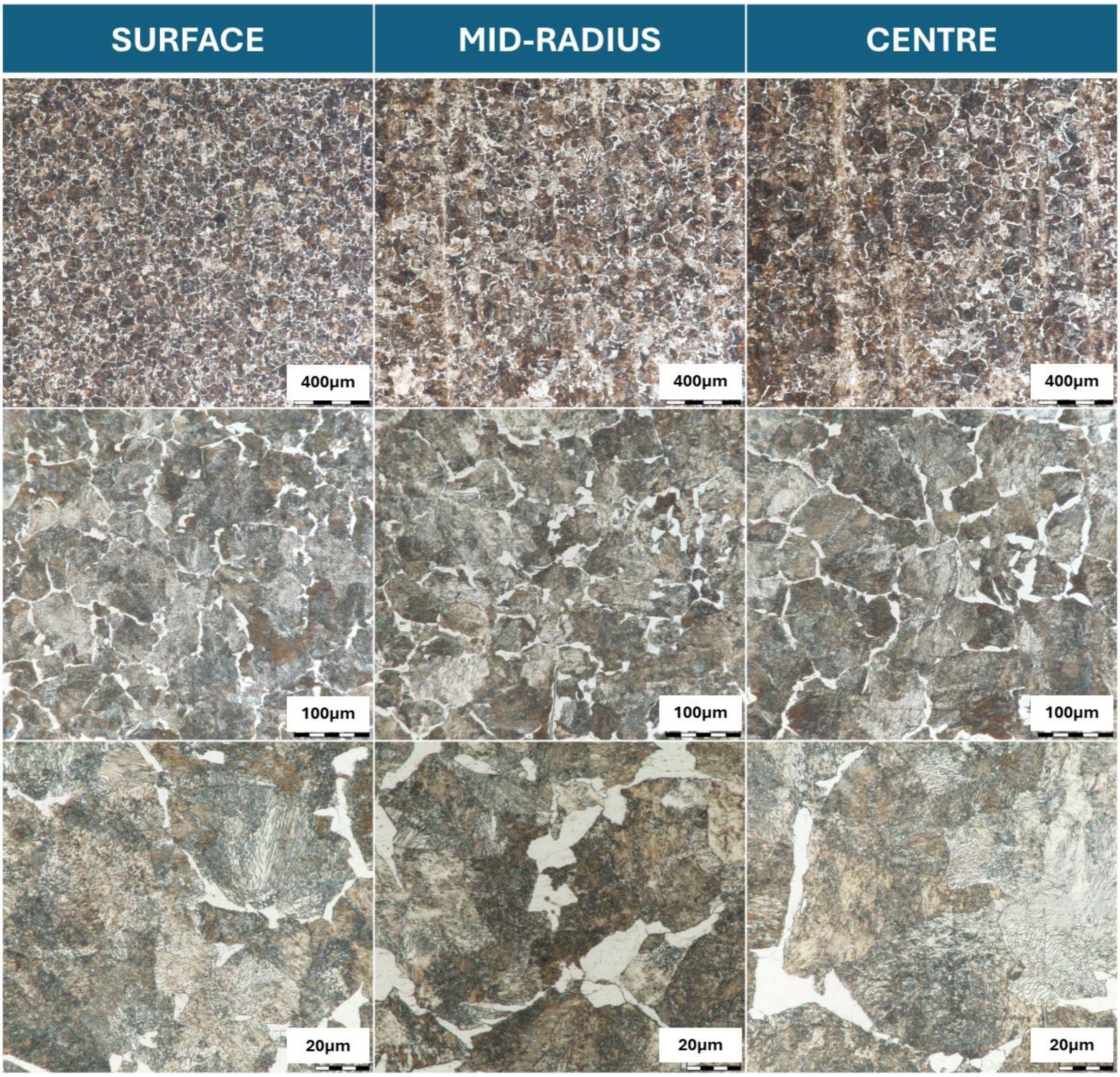

Figure 13: Microstructures obtained at the bar surface (left), mid-radius (middle) and centre (right) for C55 steel, bar Ø 60 mm in as rolled condition.

4.1.3 Determination of the hardness profiles

Hardness profile corroborates the previously described microstructural observations, reflecting the uniform ferrite-pearlite distribution from surface to core.

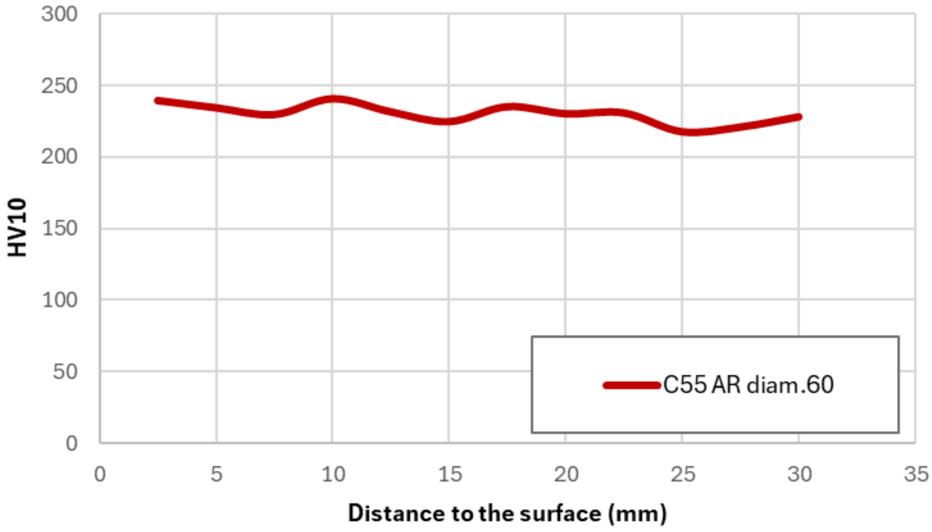

Figure 14: Hardness profile obtained for G55 steel – Route 3 in as rolled conditions (AR).

4.2 Tempering curves

As previously explained, same tempering procedure was also followed for Route 3, ensuring coherence in the characterization methodology across all selected steel grades.

4.2.1 Hardness and toughness tests

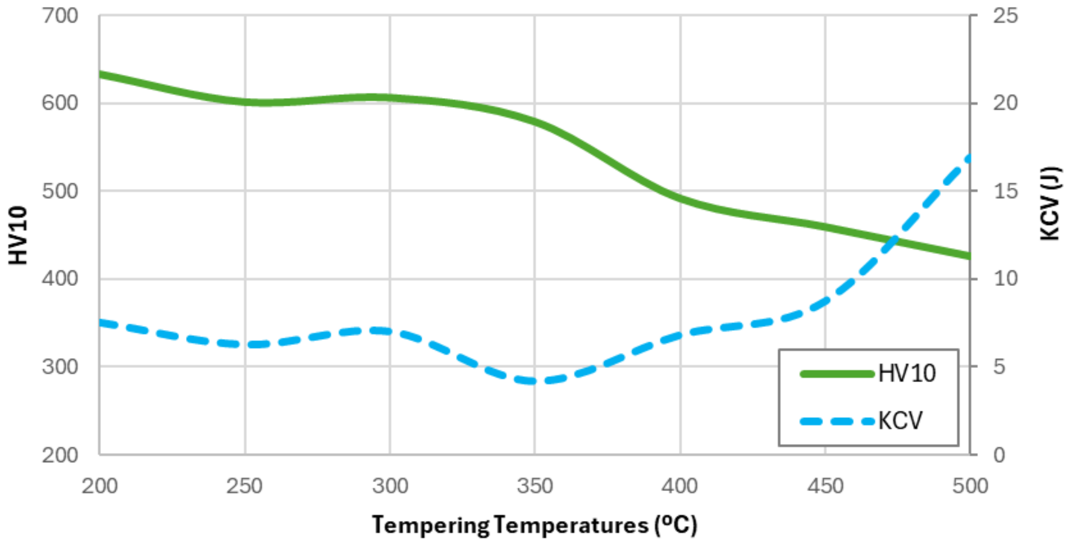

Figure 15: Hardness and toughness results for C55 at different tempering temperatures.

4.2.2 Tensile tests

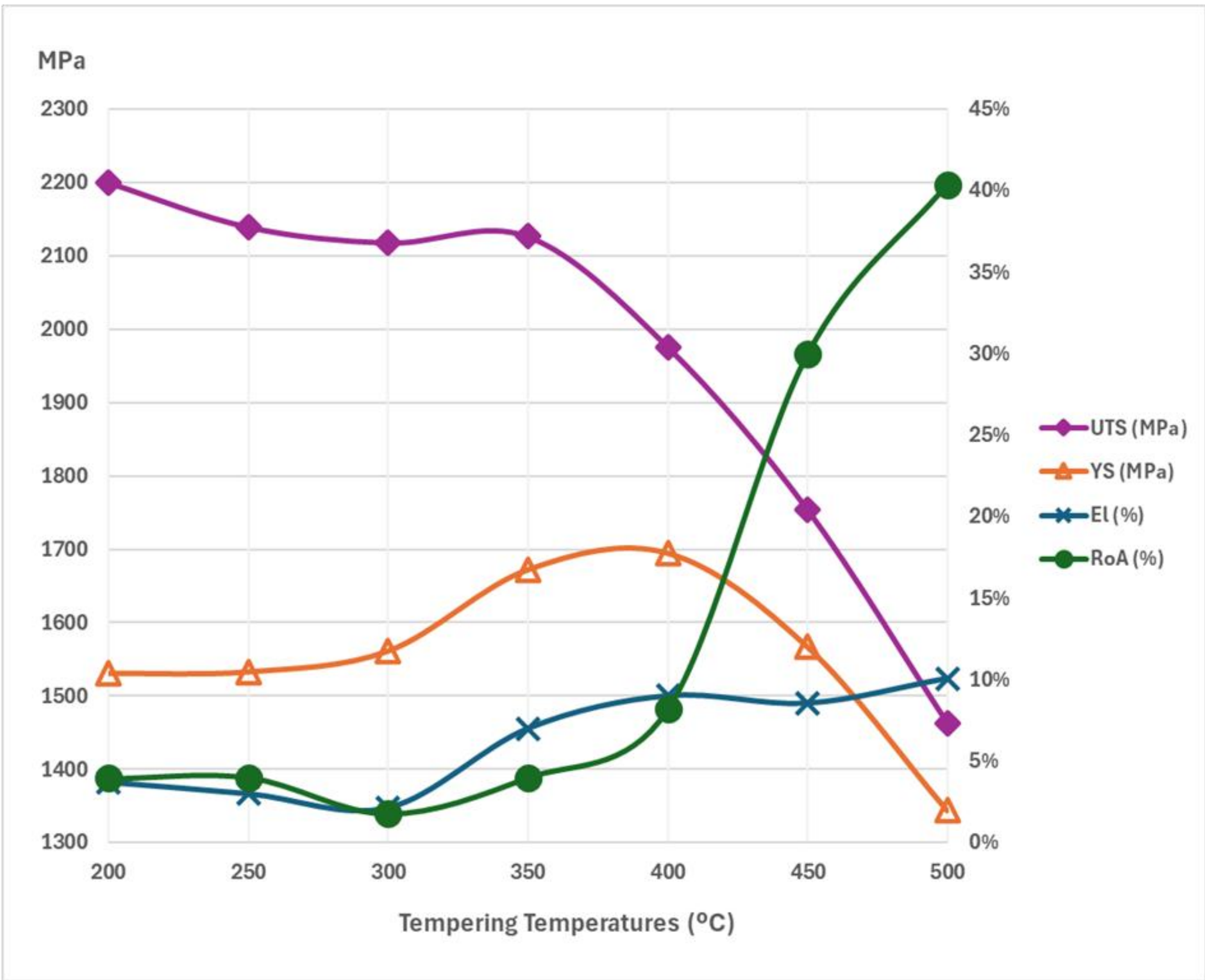

Figure 16: Tensile results for C55 at different tempering temperatures.

4.2.3 Microstructural evaluation

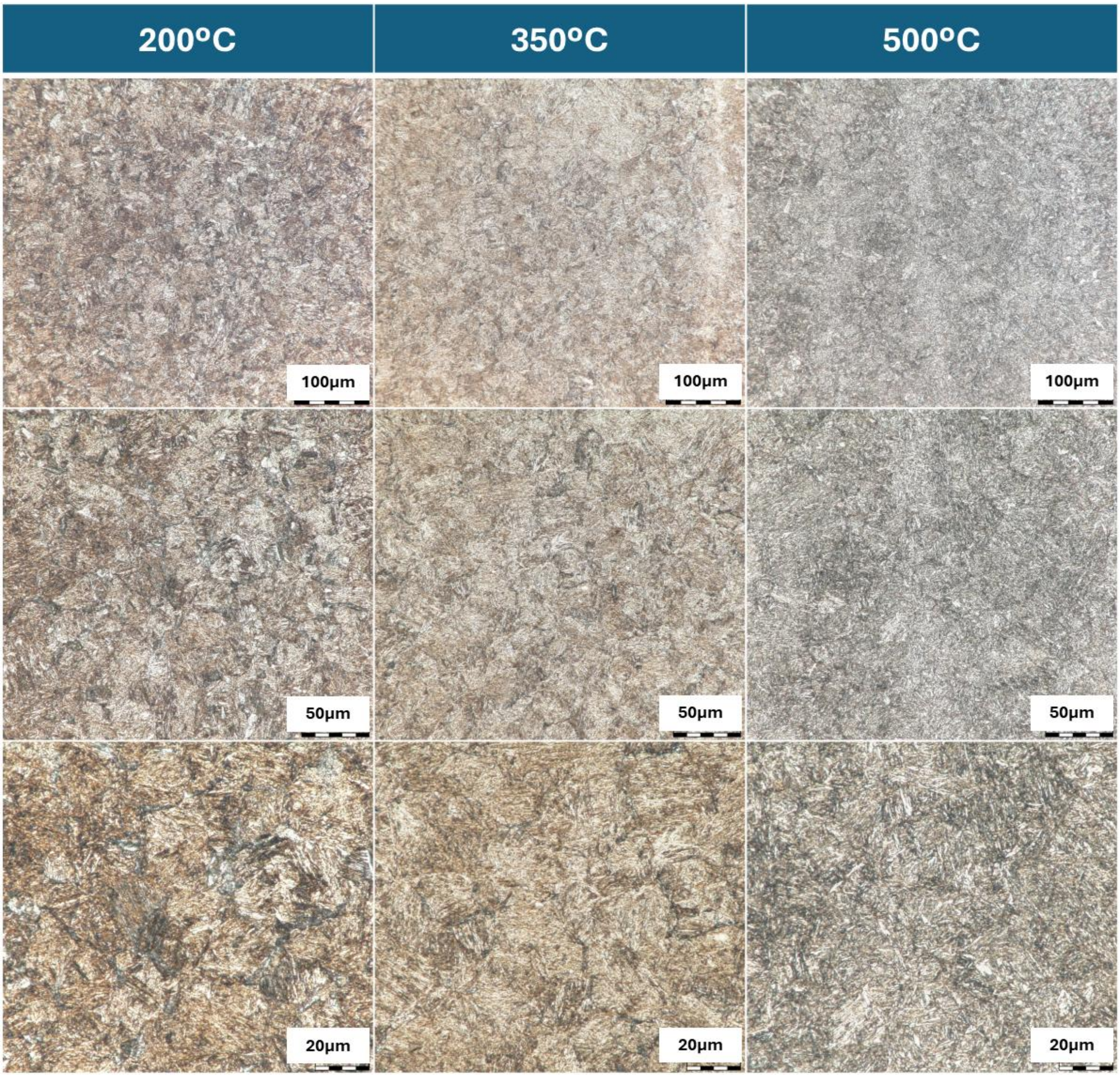

Figure 17: Examples of microstructures obtained at tempering temperatures of 250ºC (left), 350ºC (middle) and 500ºC (right) for C55 steel.

5 Conclusions

This deliverable presents a detailed metallurgical characterization of the three steel grades selected for the project, each corresponding to a different heat treatment route: case hardening – 27MnCr5, conventional quenching and tempering – 42CrMo4, and surface induction hardening – C55. The analyses included chemical composition, microstructural evaluation, hardness distribution, and mechanical property assessment (tensile and impact tests) at different tempering conditions.

Microstructural analyses confirmed that applied heat treatments led to the expected phase transformations for each steel grade. Starting from ferrite-pearlite structures in 27MnCr5 and C55, and a bainitic microstructure in 42CrMo4, all grades were successfully transformed into tempered martensite through quenching and tempering process at different tempering temperatures. In all cases, the resulting microstructures were homogeneous across the entire section, as verified through optical microscopy and supported by the uniformity of the hardness profiles.

In the three steel grades, the tempering process resulted in the expected inverse relationship between hardness and toughness: as the tempering temperature increased, a progressive decrease in hardness was observed, accompanied by a corresponding improvement in impact toughness. This behaviour is coherent with the tempering of martensitic structures, where, at higher tempering temperatures, carbon atoms diffuse more readily out of the supersaturated martensite, precipitating in the form of fine carbides. This carbide precipitation, along with the reduction of internal stresses, softens the matrix while enhancing ductility and toughness.

A similar trend was observed in the tensile tests, where increasing the tempering temperature led to a gradual reduction in tensile strength, particularly evident beyond intermediate tempering ranges. This drop in strength is attributed to the same tempering phenomena, as the dislocation density decreases and the matrix becomes more stable, the steel loses strength but gains ductility. This softening is reflected in the increase in reduction of area, indicating improved plastic deformation capacity at higher tempering temperatures.

- In Route 1 – 27MnCr5, the effects of tempering started to appear progressively from 300°C onward.
- For Route 2 – 42CrMo4, similar changes initiated at 300°C; however, they intensified significantly at higher tempering temperatures, especially beyond 400°C.
- In Route 3 – C55, a sharp transition was observed between 350ºC and 400ºC.

Only in the case of C55 steel was a clear increase in elongation observed with rising tempering temperature. This behaviour suggests that, for the other two steels (27MnCr5 and 42CrMo4), the tempering temperatures applied may not have been sufficiently high to induce noticeable changes in this specific property. Elongation, while related to ductility, is less sensitive to microstructural refinement than reduction of area and often requires more extensive softening of the matrix to exhibit significant variation.

The metallurgical characterization carried out in this deliverable establishes a comprehensive understanding of the initial properties of the three selected steel grades, each tailored to a specific heat treatment route within the project. Notably, the studied tempering range corresponds to the temperatures relevant for warm peening applications, ensuring the direct applicability of these results to next stages of the project, particularly process development (WP3) and demonstrator validation (WP5) within the ShotTempering framework.

6 References

[1] ISO 14284: 2022: "Steel and iron – Sampling and preparation of samples for the determination of the chemical composition". 2022.

[2] ISO 377: 2017: "Steel and steel products - Location and preparation of samples and test pieces for mechanical testing" 2017

[3] ISO 6507-1:2023 "Metallic materials – Vickers hardness – Part 1: Test method". 2023.

[4] ISO 148-1:2016 "Metallic materials – Charpy pendulum impact test – Part 1: Test method". 2016.

[5] ISO 6892-1:2019 "Metallic materials – Tensile testing – Part 1: Method of test at room temperature". 2019.

7 Acknowledgements and disclaimer

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Abbreviations and Definitions

Term	Definition
AR	As Rolled Conditions
El	Elongation
EV	Electric Vehicle
ISOT	Isothermally Annealed Conditions
KCV	Charpy V-notch impact energy
RoA	Reduction of Area
UTS	Ultimate Tensile Strength
YS	Yield strength

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