

Macroscopic and Microstructural Changes in S355 Steel Welded Joints under Different Fire Scenarios

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Abstract

Post-fire assessment of welded steel structures requires knowledge of whether fire exposure may cause permanent changes in the weld and its vicinity. This study examines macro- and microstructural changes in full-penetration butt welded joints made of S355J2+N steel after controlled thermal exposures representative of selected fire-related scenarios. The aim was to determine how maximum temperature, exposure time, and cooling method affect the weld metal, heat-affected zone (HAZ) and base material. Welded joints, prepared in 16 mm plates, were heat-treated at 600°C and 800°C, held for 1 h or 10 h, and cooled freely in a muffle furnace or rapidly in water mist. Etched cross-sections were analysed by optical microscopy. Results showed that short subcritical exposure caused no significant macro- or microstructural changes, whereas prolonged heating below A_{c1} promoted cementite spheroidisation in pearlite and formation of a ferritic–spheroidite structure. Exposure at 800°C, i.e. within the intercritical A_{c1} – A_{c3} temperature range, led to extensive microstructural transformations, with the final microstructure governed mainly by cooling rate. Thus, at 800°C, restructuring of the weld and HAZ becomes more likely, especially after rapid cooling. The originality of the study lies in comparing different fire scenarios for welded joints rather than base steel alone. The findings may support post-fire diagnostics of welded structures and indicate that mechanical testing is needed to relate structural changes to residual load-bearing capacity.

Keywords:

welded joints, S355 steel, post-fire, macrostructure, microstructure

1. INTRODUCTION

Fire is one of the most severe accidental actions to which building structures may be exposed. Due to its unpredictable course, locally variable temperature distribution and the possibility of permanent material degradation, the safety assessment of structures after fire exposure constitutes an important engineering issue.

In steel structures, connections are of particular importance, since their properties largely determine the global reliability of the load-bearing system. This applies especially to welded joints, in which a local, permanent change in the material structure occurs at the manufacturing stage as a result of the high temperature generated during welding, both in the weld metal itself and in the heat-affected zone adjacent to the weld. The impact of a fire episode on a previously executed welded joint should therefore be treated as a subsequent stage of its exposure to elevated temperature, resulting in further microstructural changes and, consequently, in a potential permanent change in material properties. It is therefore essential to identify the processes occurring during welding and during subsequent fire expo-

sure, as they determine the actual degree of degradation of the joint and the possibility of its further safe use [1, 2]. The temperature evolution in a material under fire conditions is inherently random; however, it can generally be stated that these temperatures are lower than those generated in the weld during the welding process.

In the literature concerning the behaviour of welded joints after fire exposure, it is increasingly emphasised that the assessment of mechanical property changes alone is not sufficient to clearly determine the degree of joint degradation. Macrostructural and microstructural analysis is of particular importance, since changes occurring in the weld metal, heat-affected zone and base material determine the subsequent hardness, strength, ductility and fracture resistance. In studies comparing GMAW and FCAW welding processes after fire exposure, Balakrishnan et al. [3] showed that, in S355J2 welded joints, an increase in maximum temperature from 300°C to 900°C leads to gradual microstructural reconstruction, depending on both the temperature and the analysed region of the joint. In the weld metal of GMAW and FCAW joints, the initial microstructure contains different ferrite morphologies, including

acicular ferrite, polygonal ferrite, grain boundary ferrite, Widmanstätten ferrite and bainite. After exposure to 300°C, mainly an increase in grain boundary ferrite and carbide segregation is observed; after 600°C, these processes become more advanced, while after 900°C, the original weld morphology undergoes substantial reconstruction towards a coarser, equiaxed ferritic-pearlitic structure. Ye and Ozaki [4] demonstrated that the microstructure of welded joints after fire exposure strongly depends on the maximum temperature and the cooling method. In the base material and HAZ, furnace cooling promoted the preservation or reconstruction of ferritic-pearlitic structures, whereas water cooling from 800 to 900°C led to the formation of mixed ferritic-bainitic-martensitic structures or fine martensitic structures. Pańcikiewicz et al. [5] also discussed the effect of long-term subcritical annealing on the microstructure of welded joints made of unalloyed structural steel. The authors indicated that, when the exposure time below the A_1 temperature is sufficiently long, the main microstructural process responsible for the observed changes is the spheroidisation of cementite in pearlite. Nasiri and Mirzadeh [6] investigated spheroidisation heat treatment of low-carbon steel and showed that holding at 700°C, i.e. below the estimated A_1 temperature, promotes the formation of spheroidised carbide particles. These observations confirm that prolonged subcritical exposure may lead to significant changes in carbide morphology, which is relevant for interpreting the microstructural changes observed after long-term heating below A_{c1} .

Therefore, understanding the processes occurring both during welding and during subsequent thermal exposure is essential for assessing the post-fire condition of welded steel joints. On this basis, the present study focuses on the macrostructural and microstructural changes in a full-penetration butt weld subjected to controlled thermal exposures representative of selected post-fire conditions. Rather than reproducing the full complexity of an actual fire event, the experimental programme was designed to isolate the effects of maximum temperature, exposure time and cooling conditions on the weld metal, heat-affected zone and base material. The resulting observations are intended to provide a macrostructural and microstructural basis for assessing the condition of welded joints after fire exposure.

2. MATERIALS AND METHODS

2.1. Material and welded joint

The weld joined steel plates with a thickness of 16 mm made of EN 10025-2 S355J2+N steel in the longitudinal direction. The joint was produced using the MAG 135 process in the PA welding position. Welding was carried out as a mechanised, robot-assisted process using a Universal Robot UR10e manipulator and a Merkle HigiPULSE 454 DW welding power source. The joint preparation involved mechanical cutting, machining and grinding. A 1.0 mm diameter Sidergas S7 filler wire, classified according to PN-EN ISO 14341-A as G 46 5 M21 4Si1, was used with M21 shielding gas composed of 82% Ar and 18% CO₂. The weld was made as a multi-run joint with

four runs, using welding currents in the range of 220–260 A, arc voltage of approximately 30.0–32.0 V and welding speed of about 22.7–23.5 cm/min. The corresponding heat input ranged from approximately 1.44 to 1.68 kJ/mm.

In the present study, controlled heat treatment was used to investigate the influence of selected thermal parameters relevant to the post-fire condition of welded joints. The adopted procedure was not intended to reproduce the complete temperature–time history of an actual fire, but rather to provide controlled and repeatable thermal exposure conditions enabling the effects of maximum temperature, exposure time and cooling method to be analysed separately. Particular attention was paid not only to the weld metal itself but also to its immediate surroundings, especially the heat-affected zone and the adjacent base material, where the initial microstructure had already been modified during the welding process.

2.2. Fire scenario simulation

The heat treatment programme was differentiated with respect to three main parameters: maximum heating temperature, holding time at the target temperature, and cooling method. Two temperature levels were selected: 600°C and 800°C. The lower temperature, 600°C, was adopted to represent subcritical exposure, i.e. heating below the austenitic transformation temperature A_{c1} . This scenario was intended to assess whether prolonged exposure below the transformation range may still lead to observable structural changes, such as recovery processes, carbide redistribution or changes in pearlite morphology. The higher temperature, 800°C, was selected as a supercritical exposure level, within the A_{c1} – A_{c3} temperature range, where partial austenitisation occurs and subsequent cooling may significantly influence the final microstructure. Heating within this temperature range promotes the transformation of pearlitic regions into austenite and progressive austenitisation of the surrounding ferritic matrix, followed by renewed transformation during cooling, which explains the pronounced microstructural reconstruction observed after exposure to 800°C. For each temperature level, two holding times were applied: 1 h and 10 h. The two holding times were selected to provide comparative short- and long-duration thermal exposures and to assess the influence of exposure time on the resulting structural changes. In all cases, the specimens were heated at a constant rate of 10°C/min until the target temperature was reached. After the required holding time, the specimens were cooled using one of two different cooling methods. The first method involved free cooling in a muffle furnace, representing slow cooling conditions. In this case, the specimens were left in the muffle furnace for 24 h, allowing them to cool down gradually under furnace conditions. The second method involved rapid cooling in a water mist, intended to reproduce an intensified cooling regime similar to that which may occur during fire-fighting operations. This approach made it possible to compare the influence of both slow and rapid cooling on the macrostructure and microstructure of the weld metal, heat-affected zone and base material after simulated fire exposure. The adopted heat treatment scheme is presented in Figure 1.

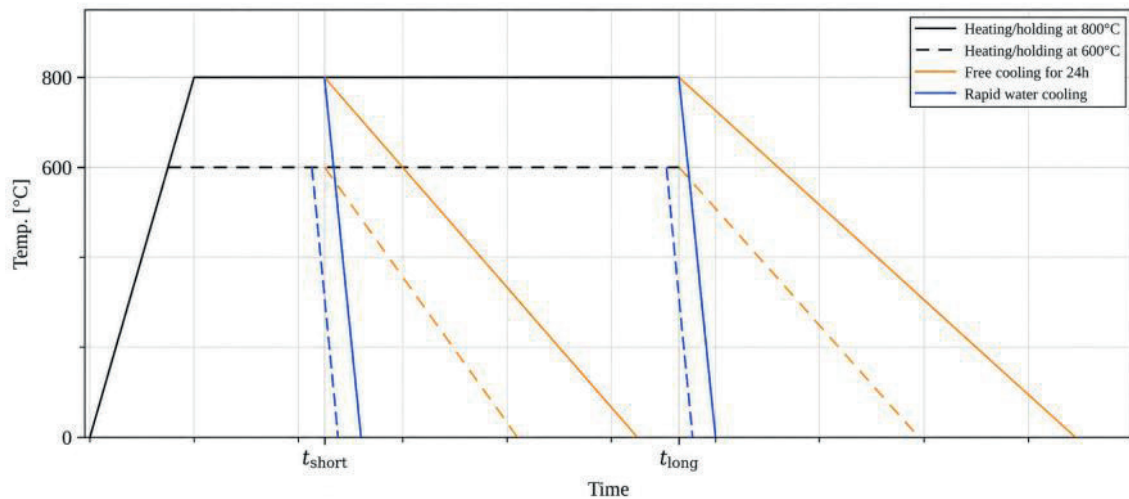


Fig. 1. Temperature–time simulation scheme for the designed fire scenarios

2.3. Equipment used in the study

The heat treatment of the samples in each considered test scenario was carried out in a KJ-M1200-64L-IC muffle furnace, as shown in Figure 2. The macrostructural analysis of the etched sample surfaces was performed using a Leica DM/LM optical microscope (Leica, Wetzlar, Germany), as shown in Figure 3a, with the use of bright field (BF), while the microscopic images presented in this paper were acquired using a Keyence VHX7000N 4K microscope, as shown in Figure 3b.

Before microscopic observations, the prepared cross-sections were etched with Nital in order to reveal the microstructural features. Different regions of the joint, varying in the distance from the heat source and in the initial microstructure formed during the welding process, were subjected to analysis. In particular, the weld metal (WM), the heat-affected zone (HAZ), and the base material (BM) were examined.



Fig. 2. KJ-M1200-64L-IC muffle furnace used for heat treatment of the welded joint samples

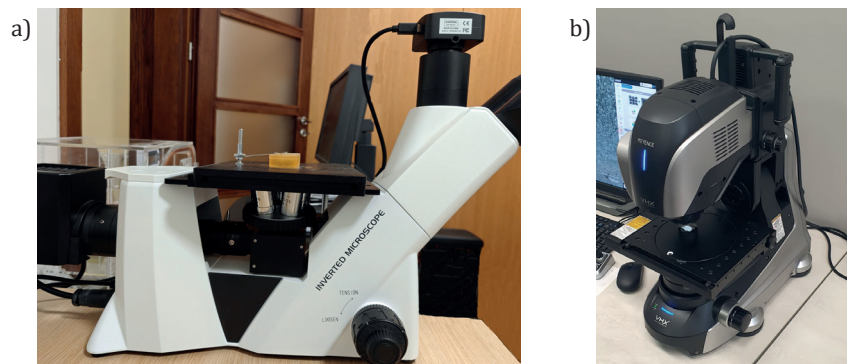


Fig. 3. Optical microscopes used for macrostructural and microstructural observations of the etched sample surfaces: a) Leica DM/LM optical microscope; b) Keyence VHX7000N 4K microscope

3. RESULTS AND DISCUSSION

3.1. Macroscopic observations

Figure 4 presents macrographs of the reference welded joint and the joints exposed to 600°C for 1 h, followed by free cooling or rapid cooling in water, respectively. The reference sample shows a typical macrostructure of a full-penetration butt weld, with a clearly visible weld metal region, heat-affected zones on both sides of the weld, and the adjacent base material. The weld face and root geometry are regular, and no macroscopic welding imperfections are visible in the analysed cross-section. After exposure to 600°C for 1 h, no significant changes in the overall cross-section geometry of the welded joint were observed. Both the weld face and the weld root retained their original shape, and the boundaries between the weld metal, HAZ and base material remained clearly distinguishable.

In the sample subjected to free cooling, the macrostructure is very similar to that of the reference joint, which indicates that short-term subcritical exposure did not cause pronounced macroscopic degradation of the joint. A similar conclusion can be drawn for the sample cooled rapidly in water after exposure to 600°C for 1 h. Although slight differences in etching contrast can be observed within the weld metal and along the HAZ, the general morphology of the joint remains unchanged.

Figure 5 presents macrographs of the reference welded joint and the joints exposed to 600°C for 10 h, followed by free cooling or rapid cooling in water, respectively. After exposure to 600°C for 10 h and free cooling, the general arrangement of the weld metal, heat-affected zone and base material remained clearly visible. However, compared with the reference sample, slight differences in etching contrast can be observed, particularly within the weld metal and along the fusion boundary. The directional structure of the

weld metal is still visible, although the contrast appears slightly more uniform, which may indicate microstructural recovery or partial redistribution of carbide phases during prolonged subcritical exposure. In the sample exposed to 600°C for 10 h and rapidly cooled in water, the macrostructure also remained generally similar to the reference joint.

Figure 6 presents macrographs of the reference welded joint and the joints exposed to 800°C for 1 h, followed by free cooling or rapid cooling in water, respectively. Much more pronounced differences can be observed after exposure to 800°C, not only in comparison with the reference sample but also in relation to all variants exposed to 600°C. In these variants, the macrostructural appearance of the weld metal and the heat-affected zone indicates a more advanced structural reorganisation. This is particularly visible in the regions corresponding to the first and the last weld passes, where the original weld morphology associated with columnar solidification becomes less distinct. The directional solidification pattern observed in the reference joint and still largely preserved after exposure to 600°C is partly blurred after heating to 800°C. This suggests that exposure to 800°C, i.e. above the austenitic transformation temperature A_{c1} , caused significant modification of the initial as-welded structure.

Despite these visible structural changes, the overall geometry of the joint remained stable. The weld face, root and cross-sectional outline did not show macroscopic cracking, discontinuities or significant distortion. Therefore, exposure to 800°C for 1 h did not visibly damage the joint geometry, but it clearly affected the macrostructural image of the weld metal and HAZ. The effect is observed in both cooling variants, although the water-cooled sample shows a slightly sharper and more heterogeneous contrast, which may indicate a stronger influence of the increased cooling rate on the final structure.

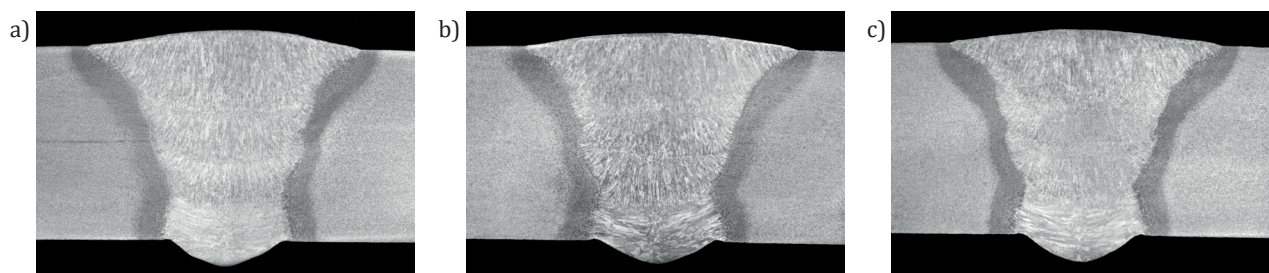


Fig. 4. Macrographs of butt welded joints: a) reference sample, without simulated fire exposure; b) sample exposed to 600°C for 1 h and freely cooled; c) sample exposed to 600°C for 1 h and rapidly cooled in water mist

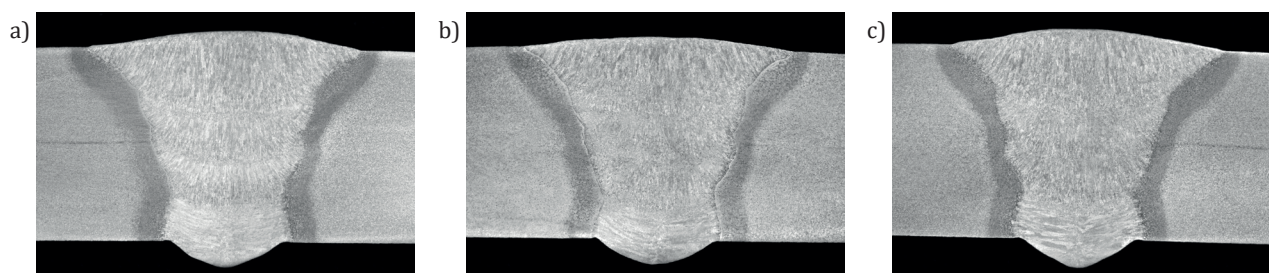


Fig. 5. Macrographs of butt welded joints: a) reference sample, without simulated fire exposure; b) sample exposed to 600°C for 10 h and freely cooled; c) sample exposed to 600°C for 10 h and rapidly cooled in water mist

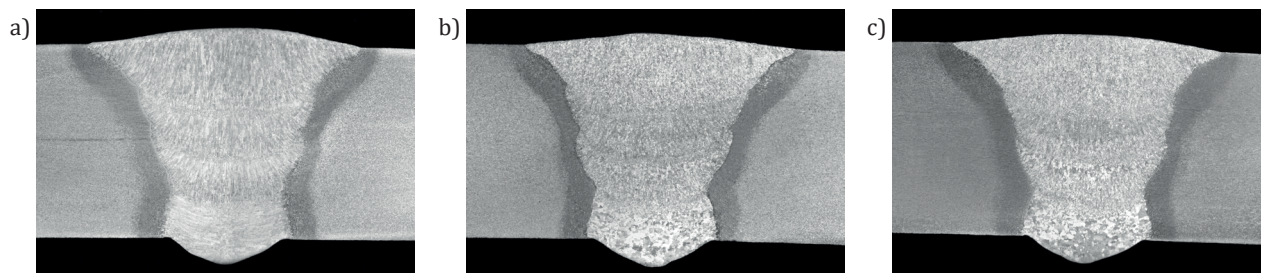


Fig. 6. Macrographs of butt welded joints: a) reference sample, without simulated fire exposure; b) sample exposed to 800°C for 1 h and freely cooled; c) sample exposed to 800°C for 1 h and rapidly cooled in water mist

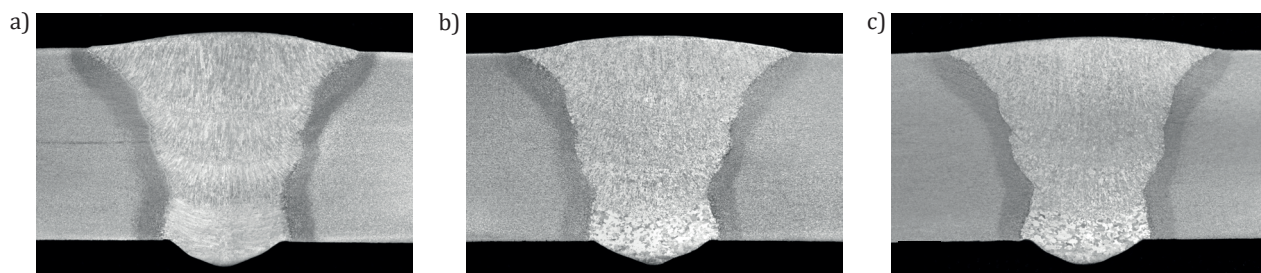


Fig. 7. Macrographs of butt welded joints: a) reference sample, without simulated fire exposure; b) sample exposed to 800°C for 10 h and freely cooled; c) sample exposed to 800°C for 10 h and rapidly cooled in water mist

Figure 7 presents macrographs of the reference welded joint and the joints exposed to 800°C for 10 h, followed by free cooling or rapid cooling in water, respectively. Compared with the reference sample, both heat-treated specimens show a clearly modified macrostructural appearance of the weld metal and the heat-affected zone, analogous to the variant exposed to 800°C for 1 h. The original directional weld morphology associated with columnar solidification is partly blurred, especially in the regions corresponding to the first and last weld passes. This confirms that exposure to 800°C, i.e. above the austenitic transformation temperature A_{c1} , leads to a noticeable reorganisation of the initial as-welded structure. At the same time, comparison with the specimens exposed to 800°C for 1 h does not indicate substantial additional macrostructural changes resulting from the longer holding time. The overall image of the weld metal and HAZ remains generally similar, which suggests that, at this temperature level, the maximum temperature and subsequent cooling conditions are more decisive than the duration of exposure.

The macroscopic observations showed that none of the analysed fire scenarios caused visible damage to the overall geometry of the butt welded joints. The weld face, root and cross-sectional outline remained stable, and no macroscopic cracks, discontinuities or significant distortions were observed. In the variants exposed to 600°C, both after 1 h and 10 h of holding, the macrostructure remained generally similar to that of the reference sample, with only slight differences in etching contrast. This indicates that subcritical exposure did not lead to pronounced macroscopic degradation of the joint. More evident changes were observed after exposure to 800°C. In these

samples, the original directional weld morphology associated with columnar solidification became partly blurred, especially in the regions corresponding to the first and last weld passes. The effect was observed for both holding times, which suggests that, at this temperature level, the maximum temperature and cooling method had a greater influence on the macrostructural appearance than the duration of exposure. Therefore, the macrographs indicate that heating in the vicinity of A_{c3} significantly modifies the internal structural image of the weld metal and HAZ, although without causing visible geometrical damage to the welded joint.

3.2. Microstructural observations

The microstructural analysis was carried out in selected regions of the welded joint, including the base metal, intercritical HAZ, fine-grain HAZ, coarse-grain HAZ and weld metal. The reference sample represents a typical full-penetration butt welded joint in the as-welded condition. A ferritic-pearlitic structure is clearly visible in the base metal, while the individual HAZ subregions show different degrees of structural transformation caused by the welding thermal cycle. The directional character of the structure formed during solidification is preserved in the weld metal.

Figure 8 presents a comparison of the reference sample and the samples exposed to 600°C for 1 h, followed by free cooling and rapid cooling in water mist. After this short subcritical exposure, the general microstructural appearance of all analysed regions remains similar to that observed in the reference joint. The ferritic-pearlitic morphology is still visible in the base metal, and the

directional structure of the weld metal is retained. Only limited changes in contrast and local morphology can be observed in the HAZ and weld metal.

The differences between the freely cooled and water-cooled samples are minor. This is because exposure to 600°C

does not exceed the austenitic transformation temperature A_{c1} ; therefore, rapid cooling does not result in hardening transformations. It can thus be concluded that short-term subcritical exposure causes only limited microstructural changes in the welded joint.

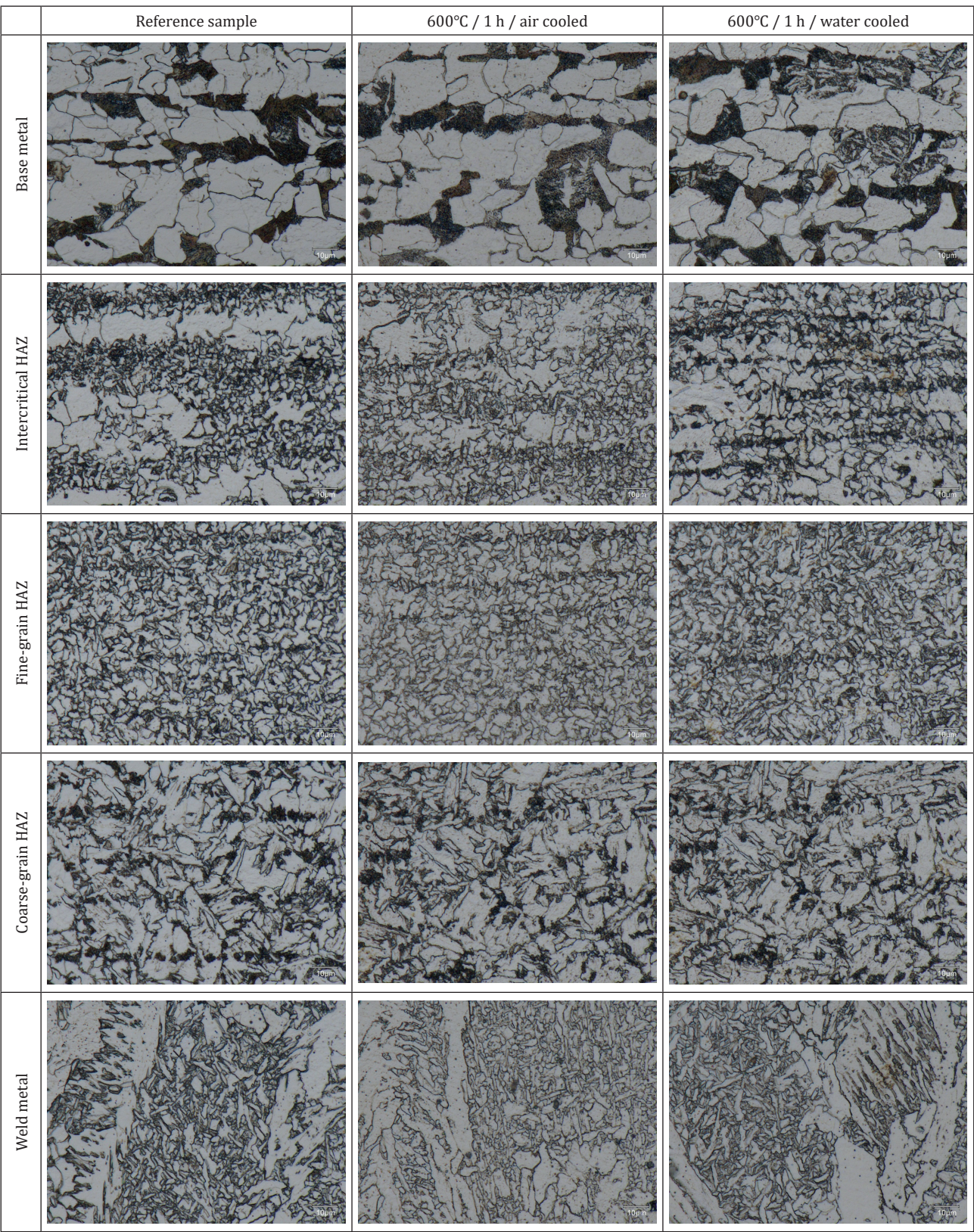


Fig. 8. Microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 600°C for 1 h followed by free cooling and water-mist cooling

Figure 9 presents the microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 600°C for 10 h, followed by free cooling or cooling in water mist. The microstructural changes are more pronounced in comparison with

the 1 h exposure experiment, although the temperature still remains below the austenitic transformation temperature A_{c1} . This indicates that, under subcritical conditions, the exposure time may play an important role in the development of structural changes.

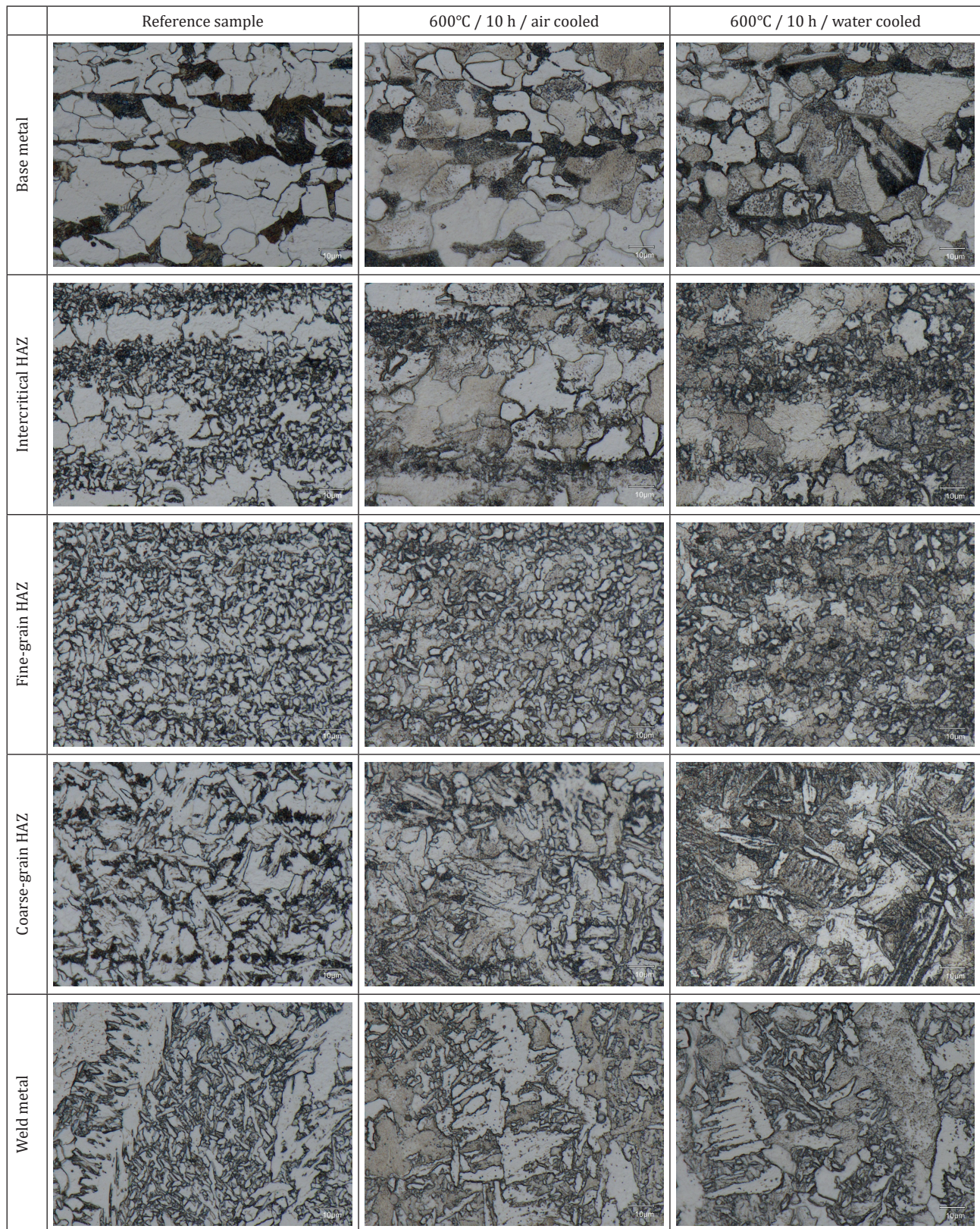


Fig. 9. Microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 600°C for 10 h followed by free cooling and water-mist cooling

The general ferritic–pearlitic arrangement is still preserved in the base metal. However, compared with the reference sample, the pearlite regions appear less compact and show more evident signs of changes. Similar changes can also be observed in the HAZ subregions, where the morphology becomes less clearly defined and the contrast of dark constituents is more dispersed. Since the exposure temperature did not exceed A_{c1} , these changes should not be interpreted as resulting from austenitisation, but rather as the effect of prolonged subcritical heating, promoting pearlite changes and carbide redistribution.

The directional character of the as-welded structure is still visible in the weld metal, although it is less distinct than in the reference sample. The darker constituents become more fragmented and locally more point-like, which is associated with the spheroidisation of cementite. The differences between free cooling and rapid cooling in water mist are still relatively limited, because rapid cooling from 600°C does not produce hardening transformations. Therefore, the observed changes are mainly related to the prolonged holding time at 600°C rather than to the cooling method itself.

Figure 10 presents the microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 800°C for 1 h, followed by free cooling or water-mist cooling. At this temperature level, i.e. within the intercritical A_{c1} – A_{c3} temperature range, distinct microstructural changes are visible in all analysed regions of the joint.

In the base metal after exposure to 800°C and free cooling, the ferritic–pearlitic character of the structure is still preserved, but the morphology is clearly modified. Larger and more regular ferrite grains can be observed, while the dark constituents are concentrated in narrower bands. This may indicate that part of the pearlite and carbon-enriched regions transformed into austenite during heating to 800°C. The austenite decomposed again into a ferritic–pearlitic structure during subsequent free cooling. Therefore, the observed structure should not be interpreted as hardened, but rather as a normalised or annealed-like structure.

In the water-cooled base metal, the dark constituents are more irregular and more strongly dispersed. Since 800°C is not high enough to fully homogenise the chemical composition, the former pearlite bands, locally enriched with carbon, could partially transform into non-equilibrium products during rapid cooling. Therefore, the dark regions observed in this variant do not necessarily correspond to typical pearlite; they may include fine products of supercooled austenite transformation, locally including martensitic or bainitic constituents.

In the heat-affected zone, exposure to 800°C caused a strong reconstruction of the initial welded microstructure. A fine polygonal structure is visible in the intercritical HAZ after free cooling. Especially fine grains occur in the regions corresponding to former pearlite, where a higher number of nucleation sites is expected due to the presence of ferrite/cementite interfaces and locally higher carbon content. As a result, this region undergoes relatively effective grain refinement after reheating and cooling.

A different behaviour can be observed in the coarse-grain HAZ. This region had already been characterised by coarser

grains and a more plate-like morphology after welding, as a result of exposure to higher peak temperatures during the welding thermal cycle. After reheating to 800°C, no similarly effective refinement is observed, probably due to the lower number of nucleation sites and partial inheritance of the previous coarse-grained morphology. After cooling in water mist, the HAZ microstructure becomes more heterogeneous, and fine, irregular transformation products are visible, suggesting that rapid cooling prevented the full restoration of a classical ferritic–pearlitic structure.

The most pronounced changes are observed in the weld metal. After exposure to 800°C, both after free cooling and water-mist cooling, the original dendritic or directional weld morphology with a significant amount of fine ferritic constituents is largely lost. Instead, the structure consists mainly of larger polygonal ferrite grains with fine dark particles or precipitates. This indicates that the weld metal was strongly modified by the applied heat treatment. Heating to 800°C caused partial or substantial austenitisation, followed by transformation during cooling into a more equilibrium structure in the freely cooled sample and a more heterogeneous structure in the water-cooled sample. Overall, the observations confirm that the final microstructure is governed mainly by the cooling method and by the initial local microstructure of each welded joint region after exposure to 800°C for 1 h.

Figure 11 presents the microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 800°C for 10 h, followed by free cooling or cooling in water mist. The observed microstructures are generally similar to those obtained after exposure to 800°C for 1 h, which indicates that, at this temperature level, the maximum temperature and cooling method have a greater influence on the final microstructure than the holding time. At this temperature, the cooling method appears to be the dominant factor controlling the final structural condition of the joint.

The microstructural observations showed that short subcritical exposure at 600°C for 1 h caused only limited changes in the welded joint. The base metal retained its ferritic–pearlitic structure, while the weld metal preserved the directional morphology formed during welding. Extending the exposure time at 600°C to 10 h resulted in more visible changes, mainly related to pearlite changes, carbide redistribution and cementite spheroidisation. However, since this temperature remained below A_{c1} , the differences between free cooling and water-mist cooling were relatively small.

A much stronger microstructural reconstruction was observed after exposure to 800°C. At this temperature, partial or substantial austenitisation occurred, especially in the weld metal and HAZ, leading to a significant modification of the initial as-welded structure. The cooling method had a greater influence on the final microstructure than the holding time in the 800°C variants. Free cooling promoted more equilibrium ferritic–pearlitic or polygonal ferritic structures, whereas water-mist cooling produced a more heterogeneous morphology with possible non-equilibrium transformation products. Overall, the results confirm that the post-fire microstructure of welded joints is governed by the combined effect of the peak temperature, exposure time, and cooling conditions,

with the strongest changes occurring after heating within the intercritical Ac_1 – Ac_3 temperature range. It should be noted that the present microstructural assessment is qualitative. Quantitative determination of grain size and phase or micro-constituent fractions was beyond the scope of this study. In particular, pearlite is a microconstituent composed of ferrite

and cementite rather than a separate phase, and its reliable quantitative assessment would require additional dedicated methods beyond conventional etched optical microscopy. Therefore, the present analysis focuses on morphological changes and the identification of the dominant transformation mechanisms.

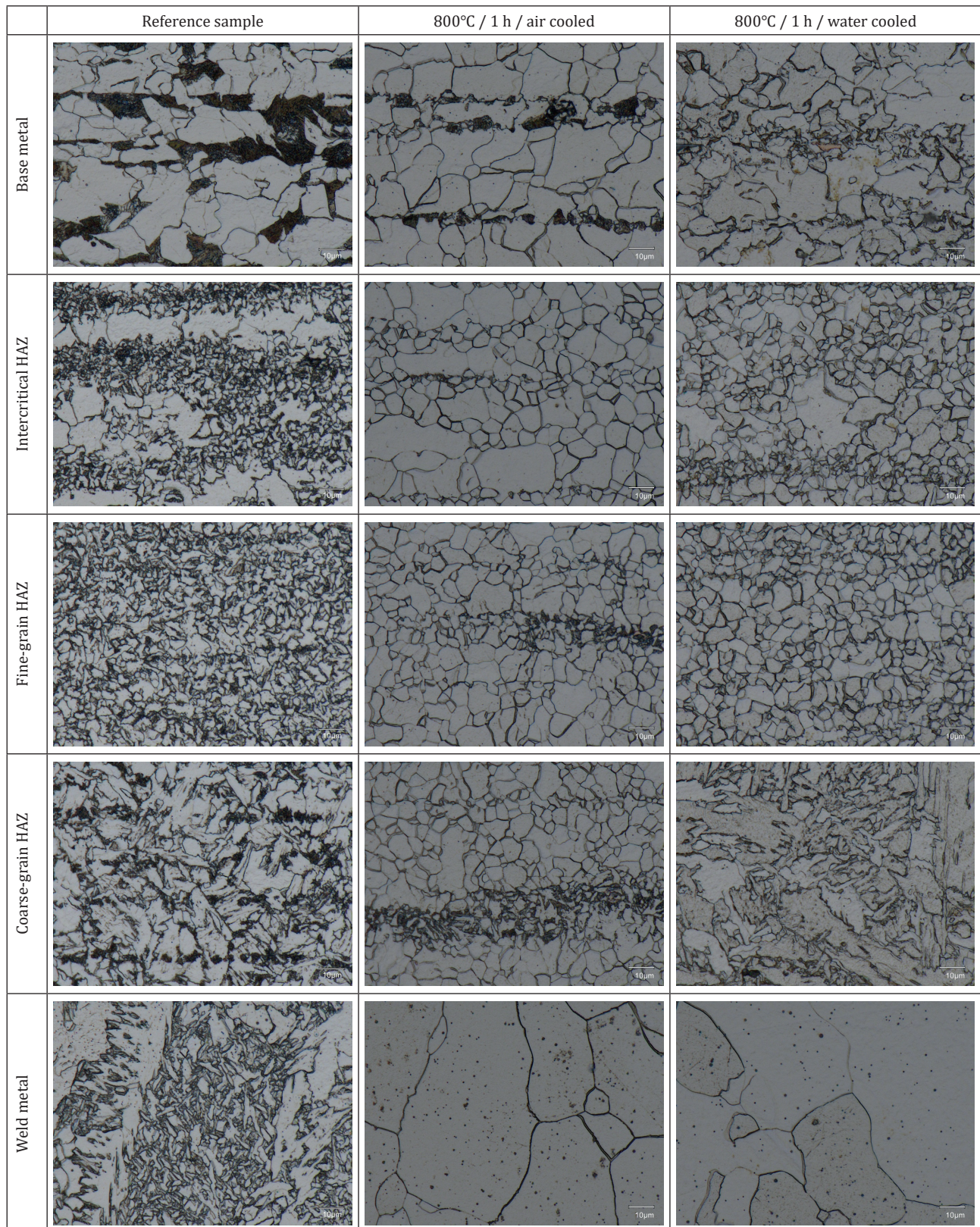


Fig. 10. Microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 800°C for 1 h followed by free cooling and water-mist cooling

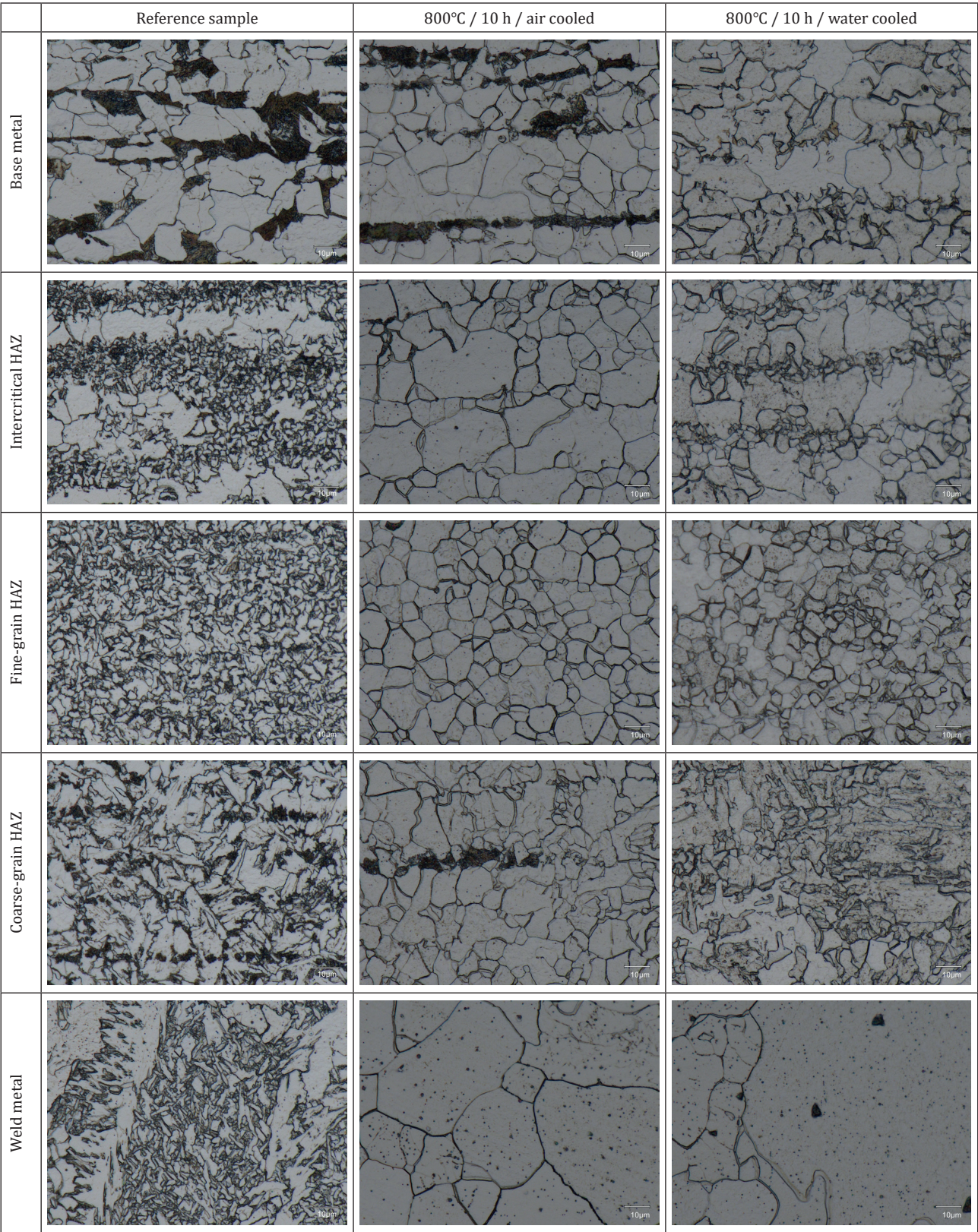


Fig. 11. Microstructural comparison of selected regions of the butt-welded joint in the reference condition and after exposure to 800°C for 10 h followed by free cooling and water-mist cooling

4. CONCLUSIONS AND SUMMARY

The conducted analysis showed that the influence of simulated fire scenarios on the macrostructure and microstruc-

ture of S355J2+N welded joints depends not only on the maximum exposure temperature but also on the holding time and cooling conditions.

The following conclusions can be drawn.

- Short-term subcritical exposure at 600°C for 1 h did not cause significant microstructural reconstruction in the base material, weld metal or heat-affected zone. The overall macrostructural image of the welded joint remained similar to that of the reference sample.
- Extending the exposure time at 600°C to 10 h resulted in more noticeable microstructural changes, mainly associated with pearlite degradation and cementite spheroidisation. This indicates that even subcritical exposure may lead to permanent structural changes if the holding time is sufficiently long.
- Exposure at 800°C, i.e. within the intercritical Ac_1 – Ac_3 temperature range, led to clear reconstruction of the initial as-welded microstructure. These changes were particularly visible in the weld metal and heat-affected zone, where the original directional weld morphology became less distinct.
- The cooling method after exposure at 800°C had a significant influence on the final structural condition of the joint. Free cooling in the furnace promoted the formation of more equilibrium ferritic–pearlitic structures, whereas rapid cooling in water mist may favour the formation of non-equilibrium transformation products.
- The post-fire assessment of welded joints should therefore not be based solely on the maximum temperature reached during fire exposure. The holding time and cooling conditions should also be considered, as these parameters determine the degree of permanent microstructural changes and may significantly affect the residual mechanical properties of the welded joint.

Further complementary studies are required to verify and extend the present conclusions, particularly by determining the mechanical properties of the welded joints after simulated fire exposure. Such tests should include hardness measurements, tensile testing, and impact toughness assessments in order to directly relate the observed macrostructural and microstructural changes to the residual mechanical performance of the joint.

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