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PHASE TRANSFORMATIONS IN A WELDED JOINT OF UNALLOYED STEEL AFTER LONG-TERM SUBCRITICAL ANNEALING

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Abstract

In the article the effect of long-term exposure of a structural weld made of unalloyed steel on permanent changes in its microstructure and mechanical properties is discussed in detail. First, the welding process itself is considered in the context of the properties of the weld obtained in it, as well as those revealed in the heat-affected zone adjacent to this weld. On this basis, a detailed analysis is carried out of possible structural changes of a permanent nature resulting from the impact of a long-term fire incident on the weld which was previously made.

***Keywords**: welded joint, phase transformation, long-term subcritical annealing*

1. INTRODUCTION

It is common knowledge that in the welding process, as a result of the impact of high temperature on the joined steel, a local permanent change in the material structure occurs, both in the weld itself and in the area of the heat-affected zone adjacent to this weld. The impact of a more or less developed fire episode on a previously made weld should be treated as another process of its exposure to high temperature, resulting in subsequent changes to the structure of this weld, and consequently potentially permanently changed its properties. The process of changes in the material temperature in fire conditions is undoubtedly random in nature. However, it can be argued that the values of this temperature are definitely lower in a fire than those generated in the weld during the welding process. In these considerations, the potential impact of a fire, both on the weld itself and on its immediate vicinity, is simulated by keeping the tested material for a long time at a fixed temperature with an intentionally selected value of 600°C. As one can see, this temperature may be interpreted as subcritical in relation to the A_1 temperature, associated for typical mild structural steel with the austenitic transformation. This method of a thermal impact formally corresponds to classical annealing of such the material. In the presented article the authors would like to show that the structure and the mechanical properties of a given weld, identified for it after a fire episode, may be significantly different from those that described the same weld before the fire [1, 2].

2. CHARACTERISTIC OF A WELDED JOINT OF UNALLOYED STEEL

A typical welded joint of unalloyed steel consists of three parts: the base material, the heat-affected zone and the weld metal. The thermal cycle of the welding process, in addition to enabling local melting of the steel, heats it to a high temperature in the vicinity of the fusion line. Moving away from this fusion line, the effect of heat impact becomes smaller. The maximum temperature obtained in a given place determines its microstructure and mechanical properties. The amount of heat input has a significant effect on the range of its impact, and consequently the width of the individual heat-affected zones, their microstructure and mechanical properties [3]. It is usually assumed that for unalloyed steels the influence on the welded material is not noted up to the A_1 temperature of 727°C. This is caused by relatively fast heating, short holding at the maximum temperature and fairly fast cooling (fig. 1a).

Above the A_1 temperature, in the area called the intercrititacal HAZ, a complete transformation of pearlite and a partial transformation of ferrite into austenite occur. Nucleation of new austenite grains causes the structure to be refined in this area. Re-cooling leads to obtaining a microstructure consisting of untransformed ferrite grains of a size similar to that of the base material and a fine-grained ferrite-pearlite microstructure formed from supercooled austenite (Fig. 1b). Reaching a temperature higher than A_3 causes the structure to be completely recrystallized – the transformation of pearlite and ferrite into austenite. As long as the temperature in the area is higher than A_3, the only existing phase is austenite. During cooling, below A_3 level, a pearlite transformation begins, leading to the formation of a ferrite-pearlite structure. If the maximum temperature is not higher than approximately 1000°C, a fine-grained structure is obtained and the area is called the fine grain HAZ (Fig. 1c), whereas if it is higher, a coarse-grained structure is obtained (coarse grain HAZ, Fig. 1d).

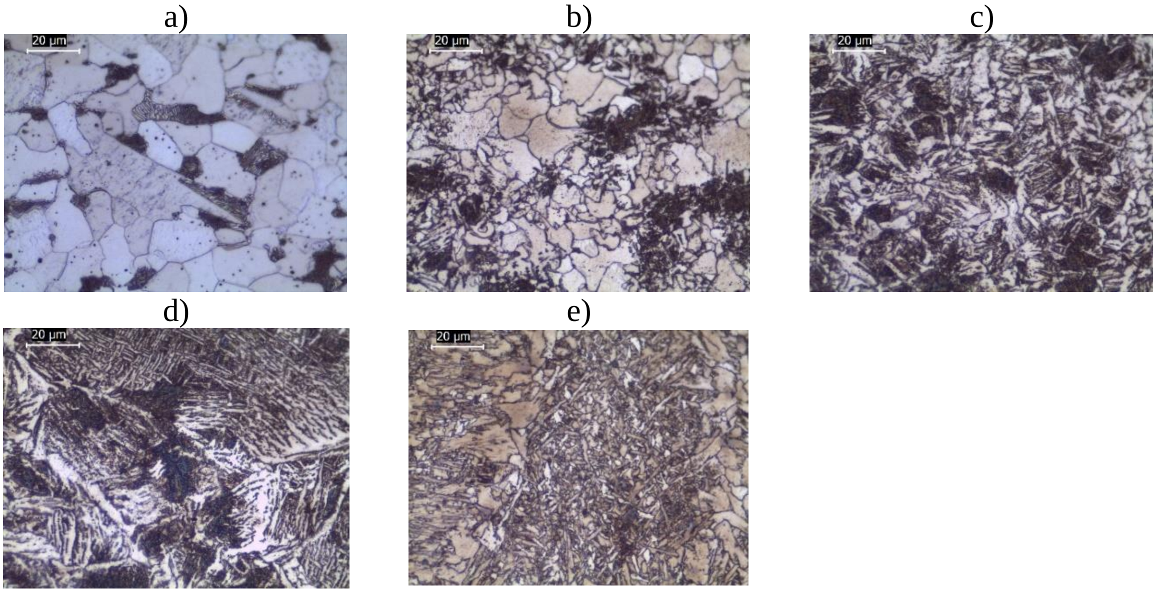

Figure 1. Microstructure of the welded joint of unalloyed steel S235JR in the as-welded condition: a) base material, b) intercritical HAZ, c) fine-grain HAZ, d) coarse-grain HAZ, e) weld metal.

A dendritic structure, characteristic of castings, is observed in the weld metal. The microstructure corresponds to the base material in terms of the obtained phases, but they differ significantly in terms of their morphology. During cooling from the liquid phase, the first nuclei of high-temperature δ-ferrite are formed, which undergo a transformation into austenite during further cooling, and then the austenite transforms into ferrite with pearlite. In this way, a microstructure is obtained with polygonal ferrite on the crystallite boundaries, from which plate ferrite (Widmanstatten) and fine-plate ferrite depart. Fine cementite occurs on the plate boundaries. Nucleation of polygonal ferrite occurs on the austenite grain boundaries when the cooling rate is relatively slow. With slightly faster cooling, the speed of movement of the ferrite grain boundary surfaces decreases, which is why side plates grow from them, growing into the austenite grains. At a higher cooling rate, the share of fine-plate ferrite increases, nucleating inside the austenite grains on small non-metallic inclusions (e.g. oxides). The cooling rate affects the weld microstructure, but consequently also its mechanical properties. An increase in the share of fine-plate ferrite has a positive effect on the impact strength of the weld. The introduction of a higher amount of heat causes a higher share of polygonal and plate ferrite, and the impact strength of the weld decreases. An example of the microstructure of a welded joint of unalloyed steel S235JR welded by the MAG method with G 42 2 M G2Si wire is shown in Figure 1e.

3. LONG-TERM SUBCRITICAL ANNEALING OF A WELDED JOINT

Fire episodes can have a significant impact on the microstructure and mechanical properties of both steel products and welded joints. Many aspects of the fire should be considered during the analysis, but the greatest impact is the effect of heat (e.g. from the flame). The behaviour during and after the fire should also be taken into account.

If this impact is not large, i.e. it causes heating of elements and welded joints made of unalloyed steel to a temperature below A_1 level and the time of such impact is relatively short, then no significant changes in the microstructure and mechanical properties are observed after the fire. Paradoxically, such an episode may even be beneficial, because after the heat impact the structure becomes relaxed, i.e. the stresses related to welding are removed.

Extending the fire time can lead to serious microstructural changes during the fire, which will also result in changes in the microstructure and mechanical properties in the post-fire state. The main phenomenon responsible for the changes will be the spheroidization of cementite (iron carbide) in pearlite. The microstructure obtained in this process is spheroidite, defined as a characteristic soft microstructure consisting of spherical cementite particles in a ferrite matrix. The spheroidization process diagram is shown in Figure 2. The microstructure of the welded joint of unalloyed S235JR steel welded by the MAG method with G 42 2 M G2Si wire after long-term holding at 600°C (> 4000 h) is shown in Figure 3.

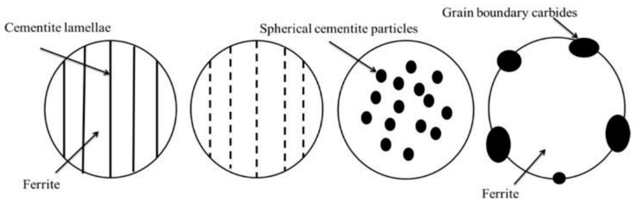

Figure 2. Scheme of spheroidization of cementite in pearlite [4].

The change in the form of cementite leads to a decrease in hardness, which has a direct impact on the change in other mechanical properties. In [5] it has been shown that for unalloyed steel after its 24 hours holding at a temperature of 700°C a decrease in hardness and tensile strength by 10% and an increase in plasticity (elongation) by 12% were observed.

In order to proceed the fastest for the spheroidization process without phase change, it is necessary to approach the temperature A_1 and next hold this temperature for a long time. Heating the considered material to a lower temperature may give the same effect but it will require more time. To calculate the equivalent time, related to an action at a lower temperature, which will give an identical effect to the analogous effect of the same action carried out for a shorter time and at a higher temperature, the Hollomon-Jaffe relationship (1) can be used, extended to include the heating and cooling time t_p (2). This leads to the final equation given in a form (3):

$$H_P = T\big(C + log(t)\big)10^{-3} \qquad (1)$$

$$t_P = T\left(2{,}3 \cdot v \cdot \big(20 - log(v)\big)\right)^{-1} \qquad (2)$$

$$H_P = T\left(C + log\big(t + t_p\big)\right)10^{-3} \qquad (3)$$

in which: H_p – Hollomon-Jaffe parameter, T – temperature (given in Kelvins), t – time (given in seconds), t_p – equivalent heating and cooling time (given in seconds), v – heating or cooling rate (given in K/h), C – constant value in the range 15-21 (for mild structural steel it is usually assumed to set 19.5) [6]. For example, keeping the material at 700°C for 24 hours will be an equivalent to analogous keeping the same material at 650°C for 345 hours and also its keeping at 600°C for 6750 hours.

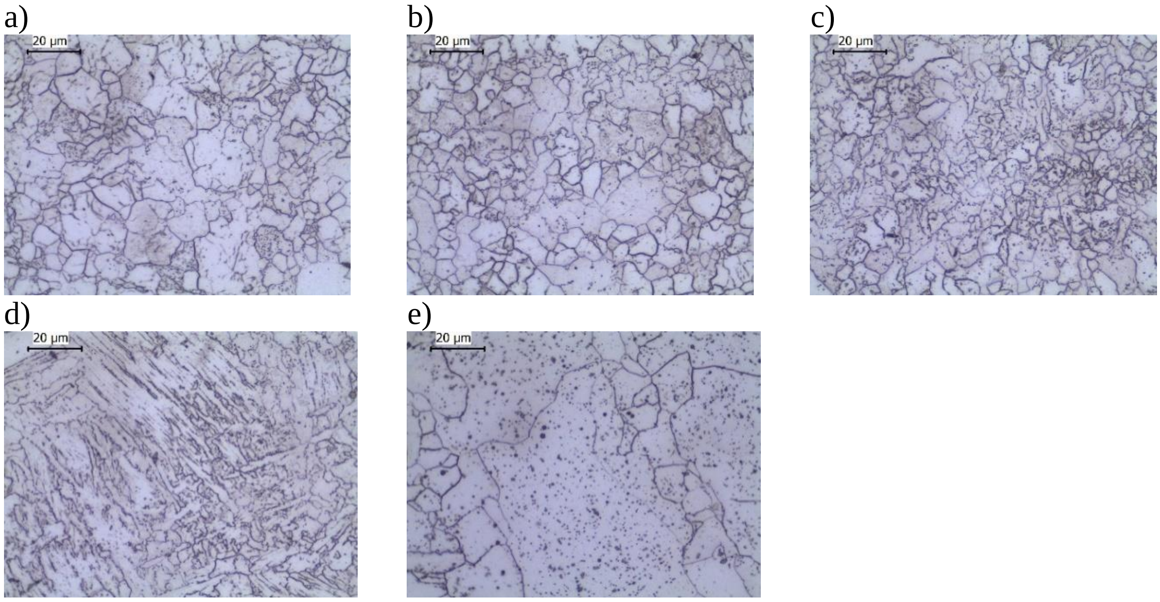

Figure 3. Microstructure of the welded joint made for S235JR unalloyed steel in the as-welded condition after its long-term keeping at constant temperature 600°C: a) base material, b) intercritical HAZ, c) fine-grain HAZ, d) coarse-grain HAZ, e) weld metal.

4. CONCLUSIONS

Knowledge of the original structure of a welded joint made in the welding process is the basis for understanding the subsequent changes occurring in the area of this joint during a fire episode. The features of such joint observed after a fire depend not only on the analogous features identified for it before this fire but also on the scenario of the fire itself. The most important parameters of such scenario seem to be the maximum steel temperature reached during a fire and also the time it was maintained in such conditions. However, the way in which the heated steel was cooled in practice is no less important in this matter. The question is whether the considered joint was cooling slowly during self-extinguishing of a fire or rather it was cooling rapidly in water mist, which usually takes place during the fire-fighting operation.

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