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Evolution of Microstructure in the Heat Affected Zone of S960MC GMAW Weld

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Abstract. High strength steels were introduced to the welded construction at the beginning of the 21st century. Phase transformation occurring in the heat affected zone of the weld significantly affects the resulting properties of the whole weld. In this study, the Gas Metal Arc Weld (GMAW) of S960MC was investigated with a special emphasis on the microstructural evolution throughout the Heat Affected Zones (HAZ). In the HAZ, three main different sub-zones were recorded. The changes of microstructures in these zones depend on the level of thermal exposure and are varying with distance from the weld metal zone. Microhardness measurements showed a decrease of microhardness in all the examined sub-zones of HAZ. The most significant decrease was recorded in the Intercritical HAZ (ICHAZ), thus it can be stated, together with the tensile tests observations, that the ICHAZ is the most critical part of the HAZ and the whole welded joint.

Introduction

In every aspect of engineering of transport vehicles, there are increased demands for the reduction of total weight for the improvement in fuel efficiency and payload capacity. High strength steels are attractive material for designers, as they are able to carry higher loadings, which allows for the reduction in thickness of used plates and therefore reduces total weight [1, 2]. High mechanical properties of these steels are obtained by combined thermo-mechanical processing to produce desirable microstructures [3, 4]. Chemical composition of high strength steels is carefully designed to allow reaching high mechanical properties while maintaining considerably low carbon content to ensure sufficient welding properties. And it is welding of high strength steels which is the main task for materialists and technologists to ensure appropriate properties of the welded parts. As mechanical properties in high strength steels are obtained by the thermomechanical processing, any heat introduced to the metal during the welding process can significantly affect the resulting microstructure and thus affect properties of the whole welded joint [5-7]. This is even more reasonable for high strength steels with the yield strength higher than 700 MPa. The S960MC steel belongs to this category. In this paper, microstructural evolution in the S960MC high strength steel welds is described and supported with the microhardness evaluation, with the aim to describe microstructural changes in all sub-zones in the heat affected zone.

Material and experiments

In the study, the thermomechanical processed S960MC steel was used. The chemical composition of the experimental material is shown in Table 1. The GMAW weld was prepared from the S960MC sheets 300×300 mm with 3mm thickness in the atmosphere of protective gas mixture M21 (82%Ar + 18%CO_2). As a filler metal, the G 89 5 M21 Mn4Ni2.5CrMo wire was used (chemical composition is shown in Table 1, and the mechanical properties are shown in Table 2).

Table 1. Chemical composition of the experimental material and filler metal.

	C	Si	Mn	P	S	V	Ti	Cu	Cr	Ni	Mo	Al	Zr
S960 MC	0.087	0.18	1.11	0.009	0.001	0.01	0.022	0.017	1.08	0.06	0.128	-	-
G 89 5 M21 Mn4Ni2.5Cr Mo	0.11	0.66	1.77	0.009	0.007	0.007	0.069	0.17	0.41	2.43	0.46	0.007	0.0019

Table 2. Mechanical properties of the S960MC base metal and the welds and the G 89 5 M21 filler metal (data were provided by the supplier).

	UTS [MPa]	YS [MPa]	Elongation [%]
S960MC base metal	1150	1034	11.5
S960MC weld metal	853	823	3.5
G 89 5 M21 Mn4Ni2.5CrMo	≥980	≥930	≥14

Single pass, but joint was performed, without any pre and post heat treatment and the applied heat input during the welding process equalled 4.3 kJ/cm. Transversal cuts were made from the weld from which the specimens for the microstructural observation were prepared, using the standard method for the preparation of metallographic specimens. Microstructural characterization was carried out using light microscopy which allows for distinguishing differences in the microstructure caused by heat affecting during the welding process. Microhardness measurements in all the individual sub-zones of the HAZ were carried out, with the used loading of 1kp. Five measurements were performed for the every identified sub-zone in the HAZ and the average values were calculated. To evaluate tensile properties of the weld and their comparison with those for the base metal, the tensile tests according to the EN ISO 6892-1 standard were carried out, and the obtained results are shown in Table 2.

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Results and discussion

Microstructural observation shows significant changes in the HAZ of the examined welds. The microstructure of the base metal is shown in Fig.1, and consists of a mixture of tempered martensite and bainite. Such a microstructure exhibits high mechanical strength while maintaining good toughness and ductility. The weld metal consists of the martensite and bainite, but no special attention was given to a weld metal, as according to the literature, the HAZ is the most problematic area in the high strength steels weld. According to the microstructure observation throughout the HAZ, several structural different sub-zones were recorded. The results of the microhardness measurements of these sub-zones are shown in Table 3. The phase transformations in the HAZ depend on the thermal exposure, to which individual parts of the HAZ were subjected and on the the time of this thermal exposure. Closer to the weld metal and fusion zone, the area was exposed to higher temperatures, but also the cooling rate was higher. In the HAZ of the examined weld, the three main sub-zones were identified (naturally, transition areas were present between these clearly distinguished sub-zones).

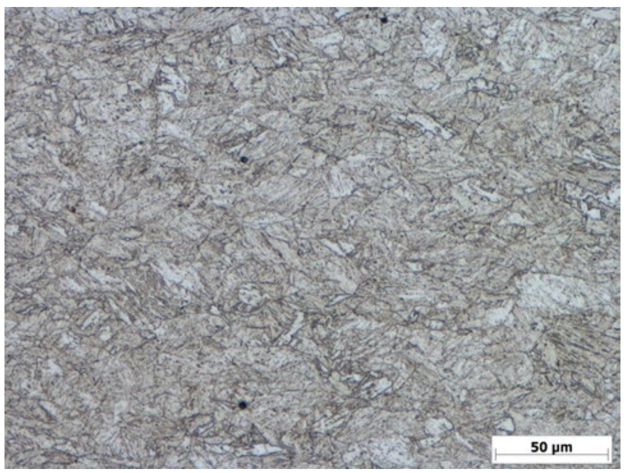

Fig. 1 Microstructure of the base metal.

In the direction from the weld metal to the base metal, the Coarse Grain Heat Affected Zone (CGHAZ) was the first distinguished zone (Fig.2c). During the welding procedure, metal in this zone was heated far above the A_{c3} temperature and thus the whole initial structure was transformed to austenite whose grains subsequently rapidly grew. Considerably high cooling rates in this area result in the formation of metastable structures such as bainite and martensite during the cooling stage. The amount of the grain growth depends on the level of overheating, and closer to the weld metal, the grain growth will be more significant. The Fine Grain Heat Affected Zone (FGHAZ) is the second resolved sub-zone (Fig.2b). The material in this zone was heated slightly above the A_{C3} temperature, but total time spent above this temperature was very short. During this thermal cycle, the material was transformed to austenite, but due to the low level of overheating, short exposure time and considerably high cooling rates, no grain growth occured. On the contrary, the refinement of the austenitic structure occurs, together with its transformation to the mixture of bainite and martensite. The last observed sub-zone, called the Intercritical Heat Affected Zone (ICHAZ) lies between the HAZ and base metal (Fig.2a). This area is very narrow (slightly more than 500 μm) and during the welding process, the thermal exposure was in the range between A_{C1} and A_{C3} temperatures. The microstructure of the base metal is partially transformed to austenite, while the rest is very strongly tempered. After rapid cooling, the austenitic part of the structure will transform to the bainite/martensite, while the rest will stay intact (it means that no visible phase transformation occurs, but strong tempering will result in significant changes of mechanical properties).

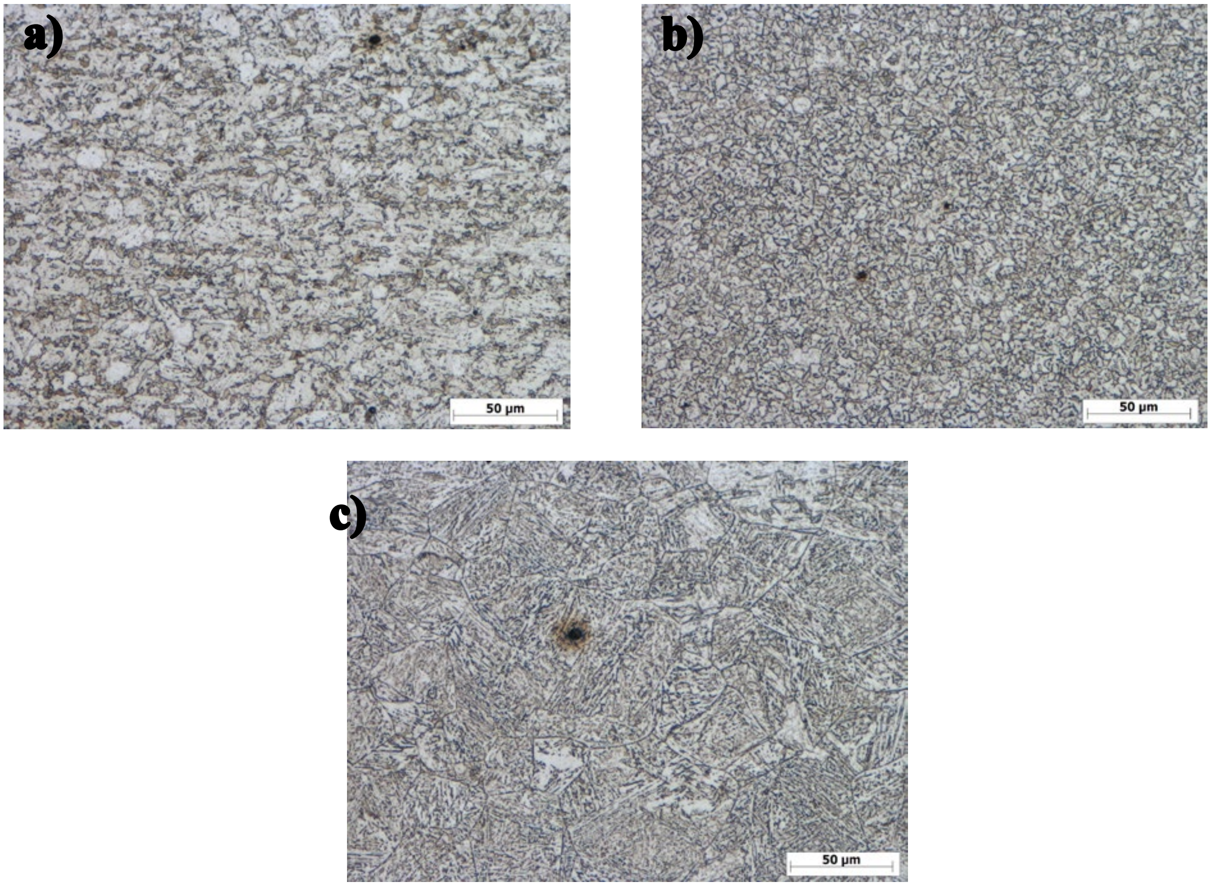

Fig. 2 Microstructure of the HAZ of the S960MC weld, a) CGHAZ, b) FGHAZ, c) ICHAZ.

The results of the tensile tests and the microhardness measurements showed several important findings. First, the tensile tests of the welded specimens showed significant decrease in the tensile strength, yield strength and also very significant reduction in the elongation of the specimens. The subsequent examination revealed that the rupture occurred in the ICHAZ in all cases. The microhardness of the base metal was almost 340 HV1, which corresponded with the microstructure of mixture of bainite and tempered martensite. In the CGHAZ, a significant decrease of the microhardness was recorded (270 HV1). This reduction of mechanical properties can be attributed to the tempering of the bainite/martensite structure and the excessive grain growth, as a result of the heat introduced to the material during the welding process. The FGHAZ also exhibited lower microhardness compared with the base metal (302 HV1), but this value is still higher than that of the CGHAZ. The decrease of the microhardness in the FGHAZ has similar reasons as that in the CGHAZ, except the grain growth (in the FGHAZ, the refinement of the grain structure was observed). The most significant reduction of microhardness was recorded for the ICHAZ. In this sub-zone of the HAZ, the value of only 228 HV1 was recorded. Similar observations were recorded by other authors [3, 5, 8, 9], the ICHAZ is the most critical part of the HAZ in high strength steels welds. In the literature, there is good agreement that the ICHAZ is the “weak point” of the weld from these steels and in most cases, the welds are broken in that area, but there is no good agreement in the description of microstructure in these areas and the explanation of low mechanical properties and ductility in this area. In the most of the available literature sources, the microstructure of the ICHAZ is described as a mixture of different types of martensite and bainite [5, 8]. In our study, the results of

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microhardness measurements suggest that microstructure in the ICHAZ cannot be considered as martensitic, due to ultra-low values of microhardness (228 HV1). The drop of mechanical properties in the ICHAZ observed in this study was larger than that observed by other authors [3, 5, 8, 9] (who used different welding methods), based on which it can be concluded that the GMAW is not an appropriate method for the welding of S960MC high strength steel. Low microhardness values in the ICHAZ suggest that strong tempering of the martensite/bainite mixture will result in the formation of difficult to describe type of ferrite-carbide mixture. This mixture cannot be considered as a martensitic nor bainitic structure, as the microhardness values are very low. The microstructure of the ICHAZ consists of a special kind of a disintegrated austenite structure (ferrite-carbide mixture), which is more similar to the unusual ferrite-pearlite mixture than to the martensite or bainite. Very low ductility is another significant property of this structure, which is a result of the reduction in elongation observed in this study, but also by other authors [3, 8]. For the determination of the exact nature of this microstructural mixture, additional tests are required, and this will be the subject of the following examinations. Even though high strength steels are used in engineering application from the beginning of the 21st century, there are still a lot of aspects, especially connected with the microstructure evolution in the HAZ, which are needed to be revealed.

Table. 1 Values of microhardness of individual sub-zones in HAZ

Sub-zone	**CGHAZ**	**FGHAZ**	**ICHAZ**	**Base metal**
Average value HV1	270.1	301.5	228.1	338.4

Conclusions

Based on the carried out experiments, the following can be concluded:

- The welding process significantly affects microstructures in the HAZ.
- In the HAZ, three main different sub-zones were recorded. The changes of microstructures in these zones depend on the level of thermal exposure and are varying with the distance from the weld metal zone.
- Observation of the three sub-zones in the HAZ was in consistency with the observations of other authors, and these were called the CGHAZ, FGHAZ and ICHAZ.
- Tensile tests showed a significant decrease of the tensile strength, yield strength and also tensile elongation. The fracture of all specimens occurred in the ICHAZ.
- Microhardness measurements showed a decrease of microhardness in all the examined sub-zones of the HAZ. The most significant decrease was recorded in the ICHAZ and thus, together with the tensile tests observations, it can be stated that the ICHAZ is the most critical part of the HAZ and the whole welded joint.
- Microstructure in the ICHAZ was a subject of increased interest in many studies, but the microstructure of this zone is still not completely clear. Based on the carried out experiments, the microstructure in the ICHAZ is some special form of ferrite-carbide mixture, but due to very low microhardness, it cannot be considered as a bainitic structure.
- Drop of microhardness values in the ICHAZ, which is more significant than that observed in other studies on a similar material suggests that the GMAW is not an appropriate method for the welding of the S960MC steel.

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