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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF WELDED JOINTS OF THOR 115 STEEL

Research was conducted on welded joints of martensitic steel Thor 115 made with two filler materials – CrMo91 and Ni 6082. The scope of the investigations included: non-destructive and destructive testing. The macro- and microstructural investigations revealed correct structure of the weld, without welding imperfections. In the joint welded with Ni 6082, the so-called Nernst's layers and δ-ferrite grains were visible. The investigations of the analysed joints showed that their properties, i.e. tensile strength and impact strength, were higher than the required minimum, whereas hardness was lower than the maximum value of 350 HV permitted for this group.

Keywords: Thor 115 steel, weld joint, microstructure, mechanical properties

1. Introduction

The environmental requirements, i.e. reduction in pollutant emissions into the atmosphere, demand the implementation of modern materials by the power industry to improve the steam parameters. The essential requirements for this type of materials include high creep and heat resistance. Creep resistance is a parameter which specifies the capacity of transferring mechanical loads at elevated temperature for a long time, whereas heat resistance refers to the material's resistance to high-temperature corrosion and the oxidising effects of steam at elevated temperature.

Past experience has shown that the ferritic-matrix steels, i.e. 9-12% Cr-type steels, can work at up to 610÷620°C. The limitation of service temperature for martensitic steels results from insufficient heat resistance in case of 9%Cr steels and reduced microstructural stability in case of 12%Cr steels [1]. In place of the material gap in this service temperature range, the austenitic steels were used. These steels were originally intended to be operated at steam temperature >650°C. Due to their adverse physical properties and reduced corrosion resistance, the use of austenitic steels gives rise to a number of operational problems [2-4]. To replace this group of steel, efforts are made to develop a material with a ferritic matrix, which would be capable of working in the temperature range of 610 (620)÷650°C. The modern material that may satisfy these requirements is Thor 115 steel. This steel, containing approx. 11% Cr, was developed as a result of modification of the chemical composition of T/P91 steel by increasing the content of chromium and optimising the content of molybdenum and niobium [3].

In addition to high requirements for mechanical properties and microstructural stability, the creep-resistant steels should also be characterised by proper processing properties, including, but not limited to, weldability. Good weldability is crucial to avoid errors, which accompanied the introduction of the T24 steel in the power industry [5]. Therefore, the implementation of new materials in the power industry requires not only to acquire the knowledge in respect of microstructural stability, but also to master the technology for making structural components, in particular using the welding technology. The purpose of the investigations was to analyse the microstructure and mechanical properties of the welded joints made in Thor 115 steel using two filler materials – CrMo91 and Ni 6082.

2. Research methodology and material for investigations

The investigations were carried out on welded joints made on Thor 115 steel tube sections of 50.8 mm (outer diameter)

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× 10.1 mm (wall thickness). Based on the recommendations of pipe manufacturer and the experience so far [6,7], the additional material used for welding was CrMo91 and Ni 6082. The welding was carried out using two filler materials – CrMo91 (joint No. 1) and Ni 6082 (joint No. 2). The test material was welded by TIG welding. After welding, the joints were subjected to heat treatment, i.e. stress relieving at 760°C for 1h.

The scope of the investigations included:

a) non-destructive testing – ultrasonic testing (UT) and radiological testing (RT),
b) destructive testing,
   - analysis of chemical composition of the base material (Table 1) and filler materials (Table 2),
   - analysis of microstructure carried out on metallographic microsections etched with iron chloride and Mi19Fe, using the optical microscopy (OM) – Axiovert 25 microscope and the scanning electron microscopy (SEM) – JEOL JSM-6610LV,
   - investigations of mechanical properties including:
     - Vickers hardness measurement with the indenter load of 10 kG (98.07 N) using FutureTech FV700 hardness testing machine,
     - static tensile test carried out at both room and elevated temperatures: 600 and 650°C,
     - impact test carried out on non-standard Charpy V-notched test specimens with reduced width of 7.5 mm.

3. Research results and their analysis

3.1. Non-destructive testing

The analysed welded joints were subjected to non-destructive testing – UT and RT, according to PN-EN ISO 16810 and PN-EN ISO 1736, respectively [8, 9]. 100% weld area was tested. The quality level B acc. to PN-EN ISO 5817 [10] was adopted as the assessment criterion and it was met for the analysed test joints.

3.2. Macroscopic examinations

The macroscopic image of the test welded joints is shown in Fig. 1. The observations of the analysed joints in given cross section showed that they had correct structure, with no visible welding imperfections in any zones of the joint, i.e. base material, heat affected zone (HAZ) and weld. This proves good quality of the joints.

3.3. Microstructural investigations

The base material, i.e. Thor 115 steel (Fig. 2), was characterised by the tempered martensite structure with numerous

TABLE 1

Chemical composition of Thor 115 steel, % wt

C	Mn	Si	Cr	Mo	Ni	Cu	V	Nb	N
0.09	0.47	0.15	11.30	0.52	0.16	0.08	0.24	0.04	0.002

TABLE 2

Chemical composition of filler materials, % wt

Filler material	C	Mn	Si	Cr	Mo	Ni	Nb	V	Ti	Fe
CrMo91	0.009	0.51	0.25	9.00	0.94	0.63	0.052	0.22	—	bal.
Ni 6082	0.035	2.99	0.08	20.00	—	bal.	5.42	—	0.35	1.27

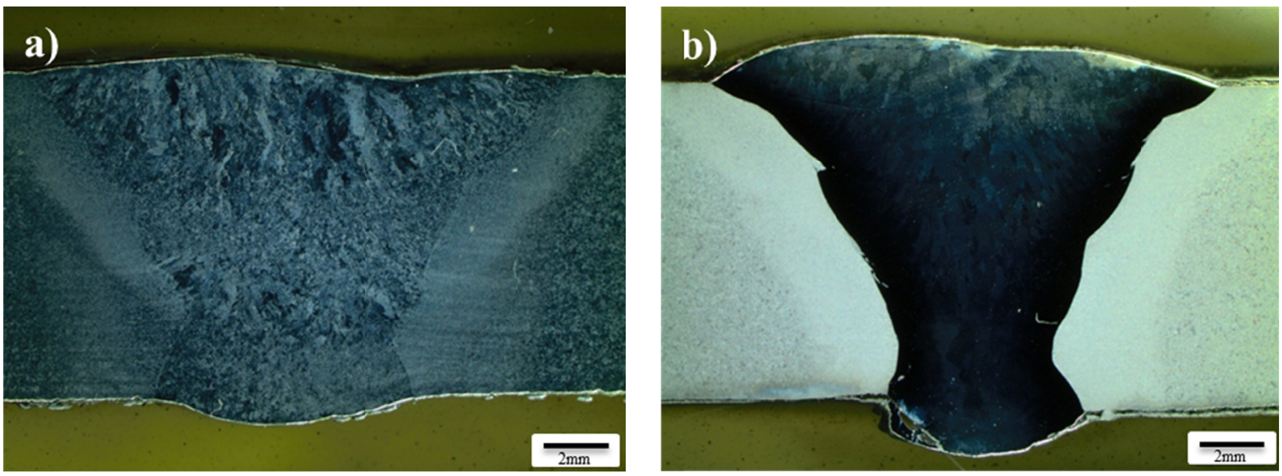

Fig. 1. Macrostructure of the joints welded with: a) CrMo91; b) Ni 6082

precipitates. The precipitate particles were observed at the former austenite grain boundaries, at the martensite lath boundaries and inside the grains. In 9%Cr-type steels in the as-received condition, two precipitate morphologies are observed: $M_{23}C_6$ carbides and dispersive MX (NbX, VX, V-wings) phases. The $M_{23}C_6$ carbides are precipitated at the former austenite grain boundaries and at the martensite lath boundaries, whereas the MX-type precipitates are observed inside the laths. Some of these particles are also precipitated on dislocations. The $M_{23}C_6$ carbides stabilise the structure of tempered martensite, while the MX-type precipitates, particularly VX particles and V-wings, are effective barriers to free dislocation motion [11,12].

The existence of various structures in the HAZ of the welded joint results from the specific nature of its formation, which is conditioned on the welding heat cycle. In general, two areas can be distinguished in the microstructure of the HAZ of the joint welded with CrMo91 (Fig. 3, 4). In the vicinity of the fusion line, HAZ area with a coarse-grained structure and numerous precipitates of different size was visible (Fig. 3). Like in the base material, these particles were mainly observed at the former austenite grain boundaries, at the lath boundaries and inside the grains. The area with the coarse-grained heat-affected zone occurs due to the impact of high thermal cycle temperature, much higher than A_{C3}, which results in the dissolution of some precipitates. The dissolution of the precipitates occurred at the grain boundaries in the matrix results in the disappearance of the pinning effect, which leads to the growth of austenite grain and, consequently, to the formation of the coarse-grained structure. The other characteristic HAZ area in Thor 115 steel was the normalisation (incomplete normalisation) area (Fig. 4). In this area, both the heat input temperature and the cooling rate are similar to the steel normalisation parameters, which contributes to the formation of the fine-grained structure. This effect is related to only partial dissolution of the precipitates in the matrix, which inhibits the grain growth. In this area, there are numerous precipitates, distributed in a similar way as in the base material. In places, the amount of precipitates at the former austenite grain boundaries was so large that they formed the so called continuous grid. A significant degree of microstructure degradation was observed in this area. Almost complete loss of the tempered martensite lath microstructure in favour of ferrite with numerous precipitates was visible. In this area, the increase in the size of $M_{23}C_6$ carbides and Laves-phase precipitates and the accelerated recovery of tempered martensite lath structure

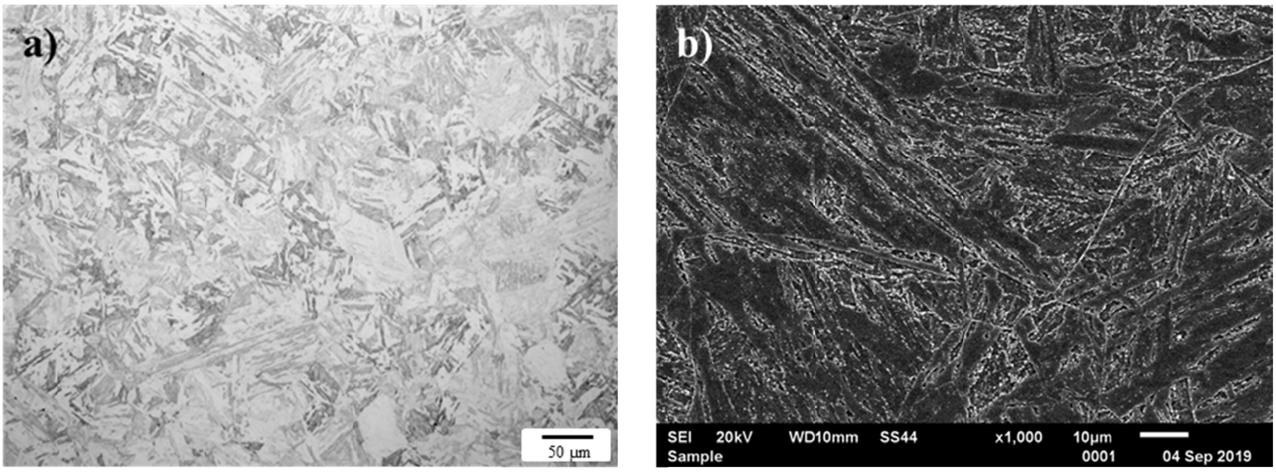

Fig. 2. Microstructure of Thor 115 steel – base material of the test joints: a) OM, b) SEM

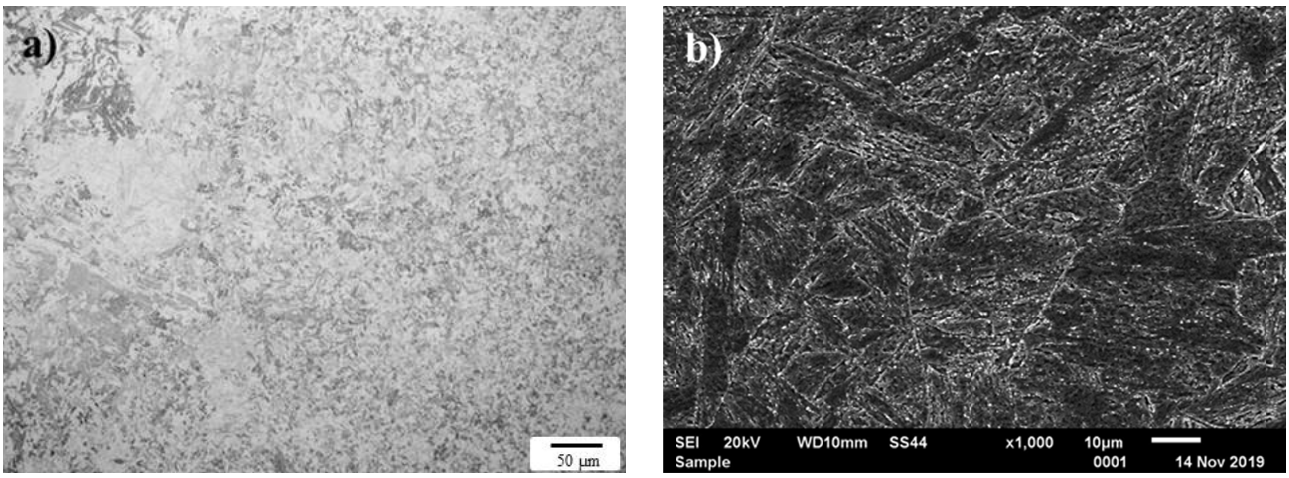

Fig. 3. Microstructure of the fusion line of the joint welded with CrMo91: a) OM, b) SEM

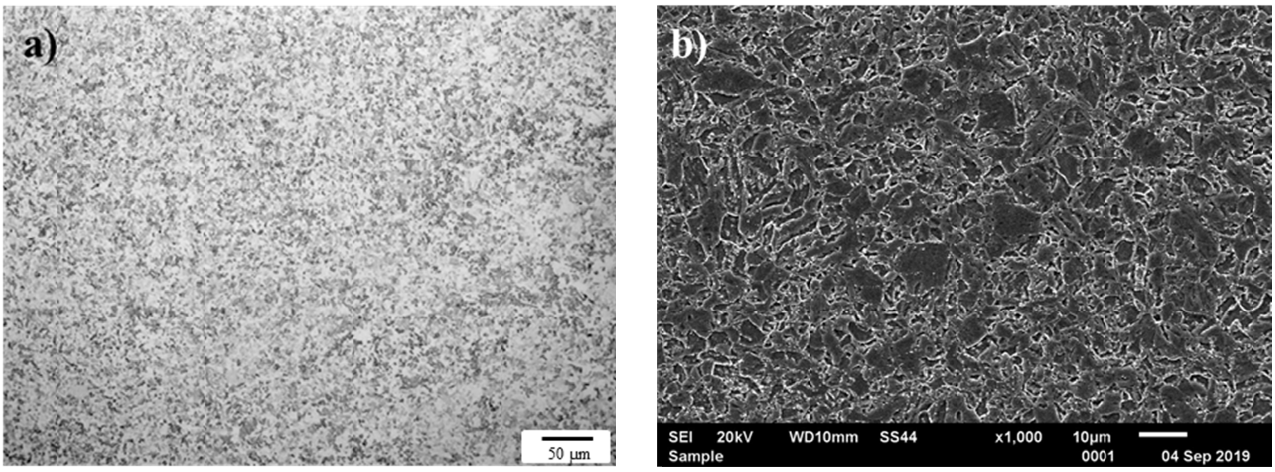

Fig. 4. Microstructure of the HAZ of the joint welded with with CrMo91: a) OM, b) SEM

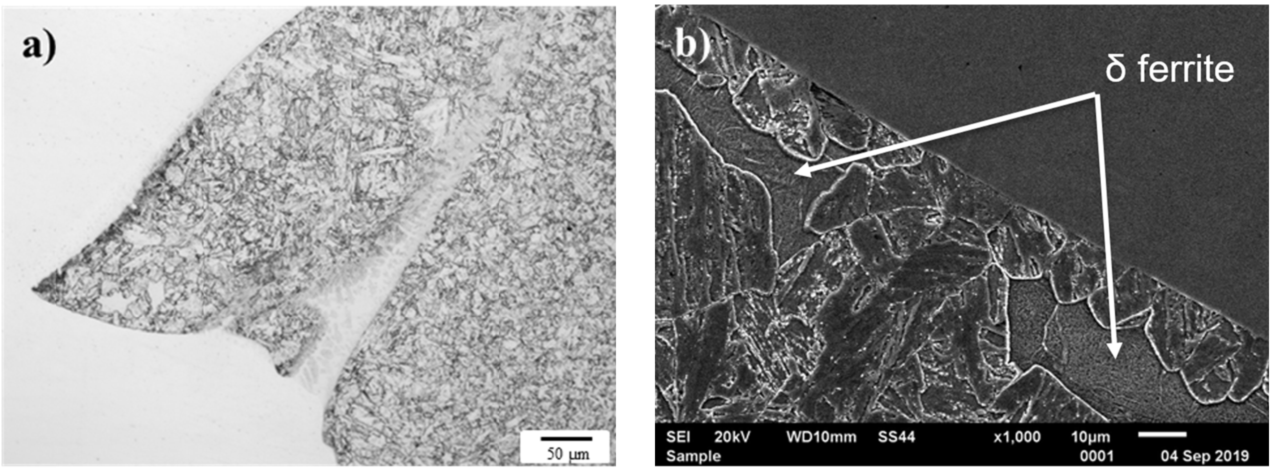

Fig. 5. Microstructure of joint No. 2 in the vicinity of the fusion line: a) OM, b) SEM

are observed [13,14]. The advanced degree of microstructure degradation in this area was related to both the effects of the welding thermal cycles and the heat treatment after welding. These processes result in softening of this area, which reduces the strength properties, hardness and creep resistance [14]. During the service, this premature effect is undesirable because it may cause premature failure of a welded construction. Such a damage during the service is called the type IV cracking [15-17].

The microstructure of the joint welded with Ni 6082 was similar to that of the previous one. The differences were in the vicinity of the fusion line (Fig. 5). At the fusion line, characteristic non-mixed areas between the weld and the base material, the so-called Nernst's layers (Fig. 5a), are observed. In addition, in the microstructure of joint No. 2, in the vicinity of the fusion line, the existence of single of δ-ferrite grains (Fig. 5b) was visible. The occurrence of δ ferrite is related to high total content of ferrite-forming elements, such as Cr, Mo, V, and Nb, in the Thor 115 steel, which favours the formation of ferrite at the fusion line. The formation of δ ferrite in TIG-welded steels is also related to the welding parameters – high heat input, cooling rate and also wide solidification range [14,17,18]. The existence of δ ferrite in the microstructure not only has an adverse impact on the toughness, but primarily on the reduction in creep strength [18]. Their occurrence is caused by the existence of a stationary liquid layer in the pool during the welding, which is adjacent to the fusion line [5,7,15]. Such areas were not observed at the fusion line for the joint welded with CrMo91 (Fig. 3). According to [19], the main problem that occurs when welding the 9-12% Cr-type steels (e.g. T/P91) with nickel-based filler material is hot cracking. This cracking was not observed in the Thor 115 steel. The microstructure of HAZ (normalisation / incomplete normalisation) in the case of joint No. 2 was similar to the microstructure observed in joint No. 1 (Fig. 4).

3.4. Mechanical properties of test joints

The results of the investigations of mechanical properties of the analysed joints are shown in Fig. 6 and referred to requirements included in [20] or presented in [21]. The fundamental investigation carried out on the welded joints was hardness measurement taken across the cross-section of the joint. The maximum hardness of the joint in the test steel (after heat treatment) should not exceed 350 HV (in accordance with [20]) – steels in material group 6 according to [22]. The measurements showed that the obtained hardness results did not exceed the maximum value. The observed differences in weld hardness in the test joints are the result of using filler materials for welding that affect the occurrence of the martensitic (joint No. 1) or austenitic (joint No. 2) microstructure. The static tensile test carried out at both room and elevated temperatures (Fig. 7) showed that the analysed joints reached the tensile strength values which are higher than the required minimum for the base material. Higher values of the tensile strength for the joints welded with CrMo91 probably result from the higher hardening of the joints, in particular precipitation hardening and grain boundary hardening, and from the refinement of microstructure by martensite lath boundaries. The results of the impact test performed on the test joints that are the measure of the material's capability of transferring dynamic loads are summarised in Fig. 8. Impact strength of metallic materials depends mainly on the grain size, but also on the precipitate morphology. Regardless of the filler material used, the impact strength of the welded joints was several times higher than that required for the base material, which is min. 52 J/cm^2. Similarly to the tensile strength, the differences in the impact strength of the weld were probably caused by the difference in grain size, but also by the presence of numerous precipitates at the grain boundaries of the joint welded with Ni 6082.

4. Conclusions

The metallographic investigations were carried out on Thor 115 joints welded with two filler materials – CrMo91 (joint No. 1) and Ni 6082 (joint No. 2). The microscopic examinations of the joints confirmed their proper structure and revealed the presence of generally two areas with different grain size and degree of degradation in the HAZ – advanced of precipitation process. The obtained mechanical properties of the analysed joints – tensile strength and impact energy – were high and exceeded the minimum requirements for the base material. Hardness on the section of the examined joints did not exceed the value of 300 HV10.

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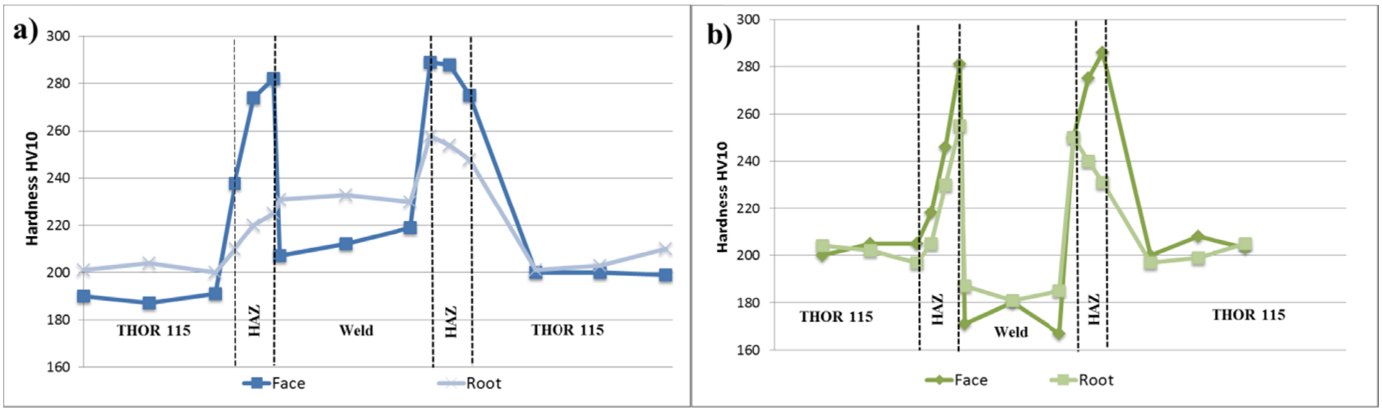

Fig. 6. Distribution of hardness across the cross-section of the joint welded with: a) CrMo91, b) Ni 6082

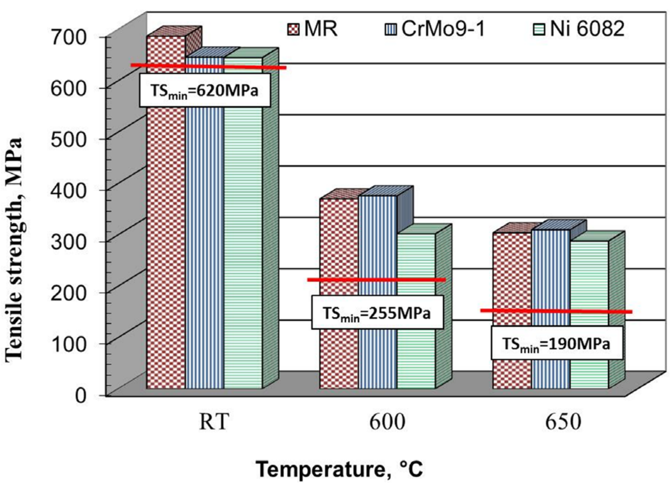

Fig. 7. Tensile strength of the test joints welded at a specific temperature

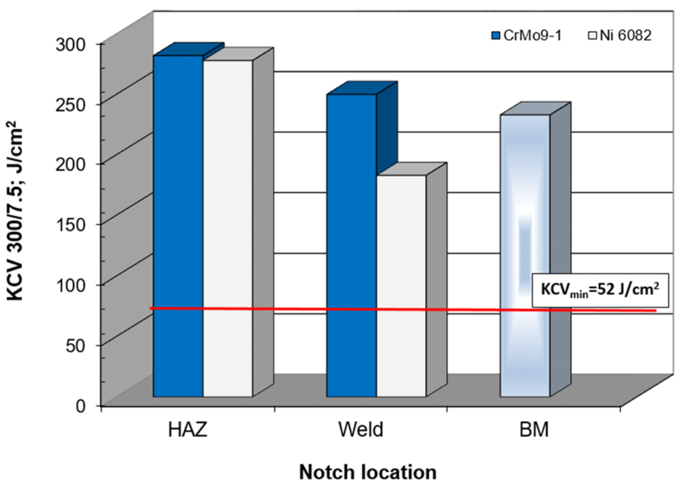

Fig. 8. Impact strength of the welded joints for both filler materials

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