EVALUATION OF HARDNESS CURVES OF MULTILAYER WELDS OF CREEP RESISTANT STEEL 1.6946 USING SAW METHOD TO THE “ULTRA” NARROW GAP

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The paper deals with partial verification of mechanical properties (through waveform measurements hardness HV10) obtained after SAW multi-pass welding in "ultra" narrow gap. Simulated homogenous welds of high pressure (HP) turbine rotors (30CrMoNiV5-11) formed with various types of filler materials (TOPCORE 838 B Thermanit MTS 616) using the same temperature cycle and subsequent heat treatment were tested. The detailed evaluation of hardness measurements HV10 was performed on the prepared metallographic test specimens. The test specimen made by Thermanit MTS 616 shows higer hardness values then the specimen made by TOPCORE 838 B.

KEYWORDS
submerge arc welding, narrow gap, low alloysteel
hardness HV10, turbine, rotor

INTRODUCTION

Energy is among one of the most important industries in the world. In view of the worldwide development if power generation, it is possible to assume a significant expansion of nuclear energy (development and application of III+ and IV generation of nuclear reactors) in the next five decades, with investments in improving the performance of power generation equipment operating on the basis of fossil fuels. This trend of improving the performance and efficiency of power generation equipment significantly increases demands on the quality of production and service life of power generation units. More specifically, it increases the demands on the innovative design of steam turbines (blades, stationary blade wheels, moving blade wheels, bearings and other parts) and their adaptation and higher resistance of materials used. Moreover, increasing demands force the manufacturing industry to adopt innovative production technologies, which are able to ensure the desired quality of the final product. Production welding technology has a major share in the production of power generation equipment and thus its performance, efficiency and lifetime as well.

Welding technology, perceived as a highly productive method of joining and surfacing material, has established its position in many industries. The progressive development of individual devices, increase in their performance, durability and serviceability simultaneously increases the demands on quality, as well as the safety of welded joints. To create a strong joint for individual parts of a rotor, it is preferable to use welding methods that allow the formation of a welded joint with the smallest possible area, in particular with the aim of minimising thermal effects on the base material [Slovacek 2007].

The research in the field of welding creep-resistant steels operating at temperatures up to 550 °C boundaries (particularly the issue of welding rotors) is at a high level. There are various national and international publications dealing with similar subjects, but until now has not given any publication describing the impact of SAW method using additional materials: Thermanit MTS 616 (ø 3.2 mm) versus TOPCORE 838 B (ø 3 mm) with subsequent use of the datas obtained for the numerical simulation of welding process [Holub 2011]. So far was not found a source that would implement a comprehensive usability evaluation of two types of welding consumables based on the analysis of the resulting internal structures of the resulting residual internal stress and mechanical properties (ultimate tensile strength, yield strength, elongation, reduction, hardness) of the multilayer-pass weld piece (base material – 30CrMoNiV5-11) [Holub 2014a], [Holub 2014b].

This article deals with only a part of the issue – changes the course of hardness in the weld metal and HAZ. These results are used as input data to verify the multilayer-pass numerical calculation that followed.

2. SAW METHOD AND DESIGN OF WELDED SURFACES

Among the best known production methods of welded joints for rotors is SAW (Submerged Arc Welding) technology. It is an automatic arc welding process that uses the intense heat generated by the electric arc (or more arcs) between the bare metal electrode (or electrodes) and the base material. The principle of arc welding under a layer of flux guarantees a suitable means of protection from airborne gases, improved purge of impurities during welding and additional alloying to the welded metal, minimum emission (UV radiation, gases formed during welding), minimised spatter of the welded metal, good bead formation and increased process efficiency. The flux performs a similar function as the containers of coated electrodes [Leblond 2003], [Esab 2009].

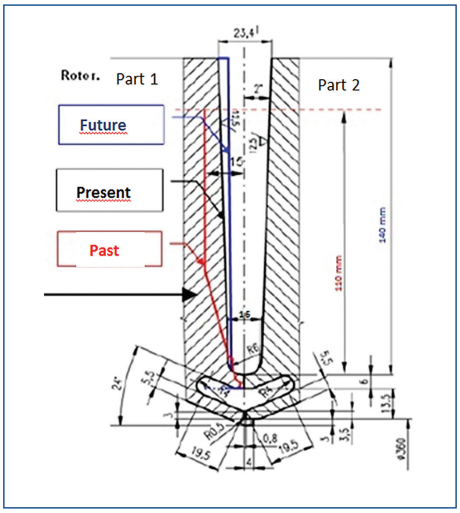

Figure 1. „ultra“ Narrow Gap

To create a high quality welded joint, it is necessary to make a suitable design of welded surfaces. For the SAW method, it is possible to apply recommendations pursuant to EN ISO 9692-2. However, a special finish of weld surfaces has been developed for this method referred to as a very narrow chamfer. Welding in a very narrow chamfer is multilayer welding with a specific chamfer of welded surfaces, whose shape is chosen so that each layer is composed of a maximum of two weld beads (width of the welding gap is usually selected between 10 – 15 mm without inclination of the welded surfaces) [Siemens IT 2009]. In our case, the special treatment of welded surfaces was applied, so-called very narrow chamfer, where the skew angle between the upper and lower edge of the weld is 0°, the selected size of the gap is 15 mm.

The purpose of combing SAW welding together with the application of an innovative weld surface is to reduce the economic demands on production in the form of reduction in welding times and a significant reduction in the amount of weld metal (i.e. filler material), while ensuring the repeatability of welding parameters of individual weld beads [Keltner 2011], [Martinec 2012] and thereby also reducing the overall thermal effects. In this case, SAW technology is preferred over the more conventional arc welding method in a protective atmosphere [Kolarik 2013] even when special functions of arc welding power sources are used [Klueh 2004]. Weld surfaces shown in Fig. 1, illustrate the past state – not used (red), current state – used to a depth of 140 mm (black) and "innovative" future state (blue). The current state representing welding in a narrow chamfer (width at root 16 mm, width on surface 23 mm) was welded to a depth of 140 mm and subsequently classified according to EN 15 613-1. The weld surface marked blue represents innovation of the weld surface in the form of a "very" narrow chamfer with dimensions; width at root 15 mm, width on the surface 15 mm, zero chamfer.

3. CREEP-RESISTANT CRMO, CRMOV STEEL

For basic classification of metal materials for the production of energy bodies (rotors) operating at higher temperatures, it is possible to use TNI CEN ISO/TR 15608: Welding – Guidelines for the inclusion of metallic materials into groups. This "Technical Report" was issued by the International Organization for Standardization (ISO) to facilitate the identification of metal materials by groups and subgroups. The classification is carried out on the basis of the chemical composition of dominant elements and alloying of the metal material. Product standards and other standards related to welding, heat treatment, NDT testing refer to individual groups and subgroups established by Directive TNI CEN ISO/TR 15608. The groups concerning steel for the production of turbine rotors with creep-resistant steel, which are classified in groups 5 and 6 according to TNI CEN ISO/TR 15608 [Pilous 2014], are provided below.

Creep-resistant steels without vanadium and with the possibility of use in temperatures up to 570 °C are classified under group 5. Creep-resistant steels with vanadium have tensile and creep values that are dependent on precipitation firming primarily through the use of Cr_7C_3 carbide (M_7C_3). They are highly ductile and during welding they are not prone to cold cracking. CrMoV and CrMoVNi steels are classified under group 6. These steels are alloyed with vanadium, which is highly active to carbon and thus together with carbon forms deficient V_4C_3 carbide and structurally stable vanadium carbide VC during cooling [Pilous 2014]. Today, the relatively outdated CrMo steels, with 2.25 wt. % Cr and 1 wt. % Mo (for example, steel T22, according to chemical composition identified as 10CrMo9-10), are replaced by new modified types with a content of alloying elements (W, Ti, Nb, N and B) that ensure higher creep resistance.

The group of modified steels is represented, for example, by steels designated as T23 (7CrWVMoNb9-6) and T24 (7CrMoVTiB7-7). The chemical composition of these steels guarantees higher resistance and a higher creep rupture strength at operating temperatures of up to 580 °C [Bendick 2007]. Other creep-resistant steels used in the production of power generation equipment are steels designated as T/P23 and T/P24. Steel T/P23 (7CrWVMoNb9-6) is an advanced, low-alloyed, creep-resistant steel that has a low carbon content together with low boron content, which ensure good weldability [Svobodova 2012], [Bendick 2007]. Steel T/P24 (7CrMoVTiB10-10) is derived the same as steel T/P23, however, with complex alloy alloying elements (V, Nb, N and Ti) ensuring the formation of MX type carbonitrides. In the case of failure to comply with a suitable temperature mode during and after welding, for all of the above mentioned steels it holds true that high Cr content (1.5 wt. %) may lead to the risk of formation of $M_{23}C_6$, M_7C_3 and MX type carbonitrides, the morphology of which consists of gross rod forms increasing firming in the heat affected zone of the weld joint

Cr-Mo steels without vanadium$^{a)}$, s C ≤ 0.35 %		
5	5.1	0.75 % ≤ Cr ≤ 1,5 % a Mo ≤ 0.7 %
	5.2	1.5 % < Cr ≤ 3.5 % a 0.7 % < Mo ≤ 1.2 %
	5.3	3.5 % < Cr ≤ 7,0 % a 0.4 % < Mo ≤ 0.7 %
	5.4	7.0 % < Cr ≤ 10,0 % a 0.7 % < Mo ≤ 1.2 %
Steels with a high content of vanadium alloyed Cr-Mo- (Ni)		
6	6.1	0.3 % ≤ Cr ≤ 0.75 %, Mo ≤ 0.7 % a V ≤ 0.35 %
	6.2	0.75 % < Cr ≤ 3.5 %, 0.7 % < Mo ≤ 1.2 % a V ≤ 0.35 %
	6.3	3.5 % < Cr ≤ 7.0 %, Mo ≤ 0.7 % a 0.45 % ≤ V ≤ 0.55 %
	6.4	7.0 % < Cr ≤ 12.5 %, 0.7 % < Mo ≤ 1.2 % a V ≤ 0.35 %
a) „without vanadium" means that the vanadium is not intentionally added to the base material		

Table 1. Creep-resistant CrMo, CrMoV steel Groups

C [%]	Si [%]	Mn [%]	Cr [%]	Mo[%]	Ni [%]	V [%]	S [%]	P [%]
0.34	0.15	0.80	1.4	1.2	0.75	0.35	0.007	0.01
–	–	–	–	–	–	–	–	–

Table 2. Chemical composition of the steel W Nr. 1.6946 [% of weight].

R_{p02} [MPa]	R_m [MPa]	KV [J]	T [°C]
≥ 550	≤ 850	≥ 24	≤ 560

Table 3. Mechanical properties of the steel W Nr. 1.6946.

R_{p02} [MPa]	R_m [MPa]	KV [J]	T [°C]
≥ 560	≤ 720	≥ 41	≤ 625

Table 6. Predicted mechanical properties of the weld metal using the welding consumable – Thermanit MTS 616.

R_{p02} [MPa]	R_m [MPa]	KV [J]	T [°C]
≥ 500	≤ 780	≥ 47	≤ 550

Table 7. Predicted mechanical properties of the weld metal using the welding consumable – TOPCORE 838 B.

C [%]	Si [%]	Mn [%]	Cr [%]	Mo [%]	Ni [%]	W [%]	V [%]	Nb [%]	N [%]	S [%]	P [%]
0.1	0.38	0.45	8.8	0.4	0.6	1.6	0.2	0.06	0.04	N/A	N/A
–	–	–	–	–	–	–	–	–	–	–	–

Table 4. Typical chemical composition of the welding consumable – Thermanit MTS 616.

C [%]	Si [%]	Mn [%]	Cr [%]	Mo [%]	Ni [%]	W [%]	V [%]	Nb [%]	N [%]	S [%]	P [%]
0.1	0.3	0.9	1.1	1.2	0.35	N/A	0.25	N/A	N/A	0.009	0.015
–	–	–	–	–	–	–	–	–	–	–	–

Table 5. Typical chemical composition of the welding consumable – TOPCORE 838 B.

[Klueh 2004], [Hu 2011]. Within the research of welding into a very narrow chamfer using the SAW method, base material W Nr. 1.6946 (material group 6, see Tab. 1) was used. It is creep-resistant, low alloy steel intended for the production of high pressure (HP) and medium pressure (MP) rotors (low alloy CrMoV creep-resistant steel with designation under the chemical composition 30CrMoNiV 5 -11), which by its chemical composition (see Tab. 2) reduces the risk of excessive precipitation of carbides compared to the above mentioned and thus ensures sufficient creep-resistance in temperatures of up to 550°C.

3.1 Typical chemical composition and mechanical properties

The work piece, (thickness of the work piece was 50 mm prepared by using base material marked like W Nr. 1.6946) was made to verify the use of a suitable filler material for multi-pass SAW welding into the „ultra" narrow gap (size of the gap follows 15/15 mm). Basically, the tested steel is the low-alloy creep resistant steel according to the chemical composition 30CrMoNiV 5-11. The flux “F25” (according to EN 760: SF AB 1 64 AC, drying prescription 350 °C – 2 hours, max. content of diffusible hydrogen 5 ml / 100 g) was used in multi-pass welding. Two types of welding consumables were examined: Thermanit MTS 616 (ø 3.2 mm, solid wire) and TOPCORE 838 B (ø 3 mm, cored wire).

The Chemical composition and mechanical properties of the base material (1.6946) are shown in Tab. 2, the typical mechanical and other technical characteristics of the flux are shown in Tab. 3 and the chemical composition and mechanical properties of the additive materials are shown in Tab. 4, 5, 6, 7 [Bohler 2005].

3.2 Weldability of the base material (W NR. 1.6946)

During the assessment of the creep-resistant steel weldability, using the above welding consumables, was necessary to consider what temperature cycles accompanying the welding process as well as subsequent heat treatment will be applied.

Low carbon welding consumables (up to 0.1% weight content) exhibit higher strength even more favorable properties during welding. According to the research [Holub 2014a], CrMoV type heat resisting steel (W Nr. 1.6946) was classified as susceptible to hot, cold cracking, for which it is necessary to follow the prescribed temperature cycles during all phases of the production process (preheating temperature, interpass temperature, controlled cooling process and heat treatment).

The Computational analysis of the base material confirmed the need of the special temperature cycle (preheating temperature, interpass temperature) and heat treatment of the work piece during the welding process because there is the danger of the internal stresses formation accompanied by the hard martensitic structures forming. To determine the temperature of preheating and the interpass temperatures were used two independent methods (Seferian´s method, normative method in accordance with EN 1011-2: 2000).

The calculation formulas given in [Kolarikova 2013], [Kolarik 2012] were used. Comparing the results of the preheating temperature was recommended to 350°C. The preheating temperature, interpass temperature selected 300 °C based on the results and through the consultations with low-alloy creep resistant steels processors (Siemens Industrial Turbomachinery). This determination is based on the consideration that when the temperature reaches less than 300 °C during the multi-pass welding process (multi-pass layer), the permitted limit of the cooling rate can crossed and the formation of the brittle layers by precipitation of solid disperse phase by alloying elements can be expected. Considering the calculated Mf temperature (Mf ÷ 100°C), the final temperature of the controlled cooling before heat treatment – was set at 150 °C – holding time 1 hour – cooling rate 50 °C / h.

The heat treatment was chosen by an appropriate combination of the recommended heat treatments for rotors´ manufacturing of the same or similar base materials. Heat treatment was applied in the same manner for both types of filler materials [Holub 2014a].

4. EXPERIMENTAL PART

Before performing penetration test plate was preheated in an electric furnace at 300 ° C, the heating time for sufficient heating of was 4 hours. The flux was dried according to the manufacturer's instructions. The multi-pass weld was made by 18 weld beads (in 9 layers) using the intepass temperature not less than 300 °C. The same laying weld beads procedure was applied for both types of filler materials. After optimization of the welding parameters [Holub 2014b], the parameters have been set: the welding current 450 A, the voltage 29 V, the welding speed 58 cm/min.

The experiment was conducted in the Laboratory of cross-faculty teaching welding technology of Czech Technical University in Prague, Faculty of Mechanical Engineering, Institute of Engineering Technology. The welding equipment and the integrated welding tractor co. ESAB type: LAF 681 with the control system PEK + A2 Multitrac was used during the experiment. The guidepath was constructed to ensure a stable conduction of the welding nozzle. During the experiment was periodically measured the value of the welding current (system Weldmonitor 4.5) and the temperature cycle was checked. Temperature check of the preheating process and the interpass temperature were carried out by the fixed thermocouple using the “ALMEMO” measuring device.

The quality requirement of multi-pass beads was determined according to EN ISO 5817 in the quality level „B“. The detailed analyzes of test welds using non-destructive and destructive tests was carried out. The Visual inspection (all made of welded layers) and magnetic powder test found no unacceptable surface (and subsurface) defects. The X-ray examinations has demonstrated satisfactory internal multi-pass joint integrity, verified by the macrosection visual testing of few samples, manufactured by the procedure listed [Kolarik 2013], [Kolarik 2014].

5. MEASUREMENT OF HARDNESS HV10

The method of choice for the hardness test was the method of measurement according to Vickers (HV) in accordance with EN 1043-1 and EN ISO 6807-1, so as to ensure the position of rows of indentations for reading measured values with weld metal, the heat affected zone and base material. During the measurement, the minimum distances between individual indentations were maintained so as not to influence the results with plastic deformation that occurs after indentation. Hardness measurement (HV10) was performed on pre-cuts (see Fig. 2, 3) using measuring device (VICKERS HPO10), where the penetrating diamond body of a regular quadrangular pyramid with a square base (apex angle of 136° ± 0.5°) was loaded with a nominal force of F = 98.07 N.

Measurement of hardness was applied to three horizontal lines of a multilayer weld (upper, middle, bottom line) and one vertical line, which copied the axis of the weld joint. The upper horizontal line was made at a depth of 2 mm, the middle horizontal line at a depth of approximately 12 mm, and the bottom line at a depth of approximately 24 mm under the surface of the base material, about 3 mm from the

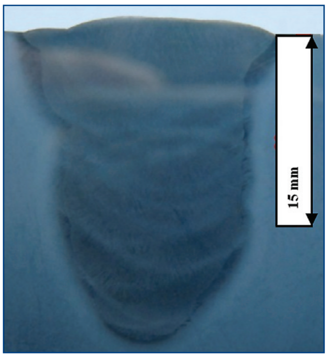

Figure 2. Specimen (PM Thermanit MTS 616)

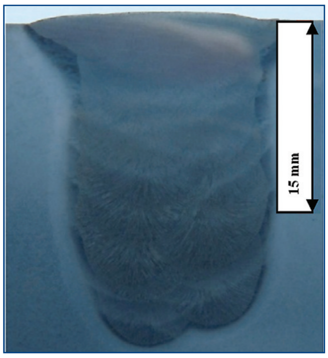

Figure 3. Specimen (PM TOPCORE 838 B)

lower edge of the "root" of the weld. The principle of measurement was carried out the same way for both metallographic samples, the diagram of lines A, B, C and D is shown in Fig. 4.

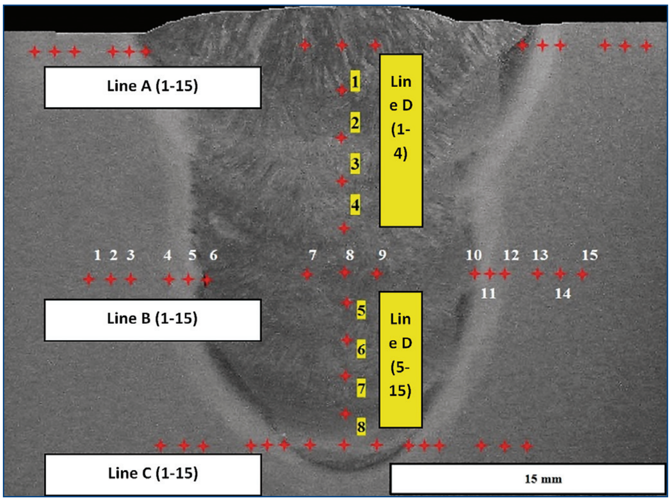

Figure 4. Measurement of hardness HV10 – diagram lines

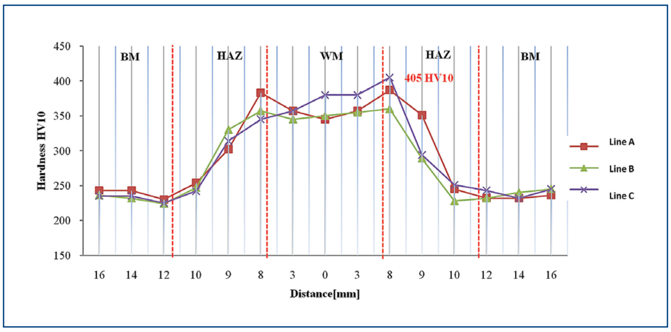

Figure 5. Hardness HV10 – line A, B, C (Thermanit MTS 616)

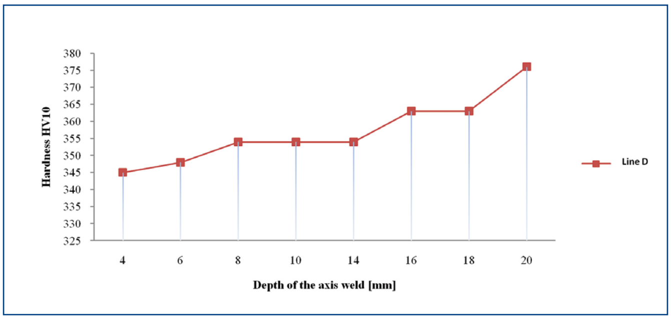

Figure 6. Hardness HV10 in the axis of the weld – line D (Thermanit MTS 616)

5.1 Results

In terms of the multilayer weld filled using filler material Thermanit MTS 616, measurement findings showed that hardness values measured in the weld metal zone on line A (upper line) range between 345 – 357 HV10, 345 – 355 HV10 on line B (middle line) and between 357 – 380 HV10 on line C (bottom horizontal line). HV10 hardness values measured in HAZ (up to 9 mm from the axis of the weld) on line A (upper line) range between 302 – 387 HV10, 289 – 360 HV10 on line B (middle line) and between 294 – 405 HV10 on line C (bottom horizontal). The hardness values of the base material are on the same level as the sample penetrated with the addition of TOPCORE 838 B filler material at around 240 HV10. The hardness values measured at the axis of the multilayer penetration (carried out with filler material Thermanit MTS 616) show higher values (between 345 – 376 HV10).

Measurement shows that in the case of the multilayered penetration filled using TOPCORE 838 B filler material, the hardness values measured in the weld metal zone on line A (upper line) are around 336 HV10, 340 – 345 HV10 on line B (middle line) and up to 349 HV10 was measured on line C (bottom horizontal). HV10 hardness values measured in HAZ (up to 9 mm from the axis of the weld) on line A (upper line) ranged up to 349 HV10, and up to 340 HV10 on line B (middle line) and line C (bottom horizontal). The hardness values of the base material are around 240 HV10. The vertical line D – copying the weld joint axis – shows dependency with increasing hardness towards the root of the multilayer weld. At the bottom part of the multilayer weld, maximum hardness of 350 HV10 was measured. Measurement revealed that in no case did the measured harness values exceed the recommended maximum allowed value of 350 HV10 (see Fig. 7, 8).

Based on the macroscopic analysis of the weld metal even in the intersection zone WM/HAZ & HAZ/BM were not found any unacceptable types of defects. The heat affected zone is uniform, and its width is 3–5 mm. The structure of the base material of both samples is in terms of the same nature. The internal sturcture is a tempered sorbite structure formed by ferritic matrix assuming evenly precipitated carbides.

6. DISCUSSION

From the above mentioned results, it is evident that the test sample made with TOPCORE 838 B filler material showed a higher hardness of up to 350 HV10 in the heat affected zone, which, however, did not exceed the maximum limit value of HV10. In terms of the test sample made with Thermanit MTS 616 filler material, results showed that the hardness values in several cases exceeded the recommended maximum allowed value of 350 HV10 (normative regulation EN 15614-1 for group 6 steel under TNI CEN ISO/TR 15608). The highest value was measured on line C in the "HAZ/WM" area of overheating, where the hardness value reached up to 405 HV10. Critical areas with higher hardness were found mainly in HAZ (area of partial smelting and overheating), where the highest hardness value reached up to 405 HV10. In agreement with the above opinions [Svobodova 2012], [Bendick 2007], this increase in hardness may be associated with a higher chromium content in the filler material in combination with the

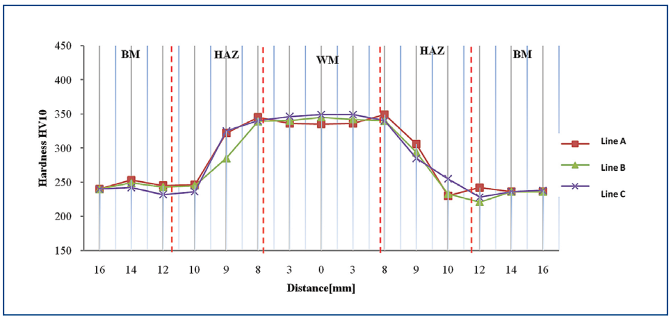

Figure 7. Hardness HV10 – line A, B, C (TOPOCORE 838 B)

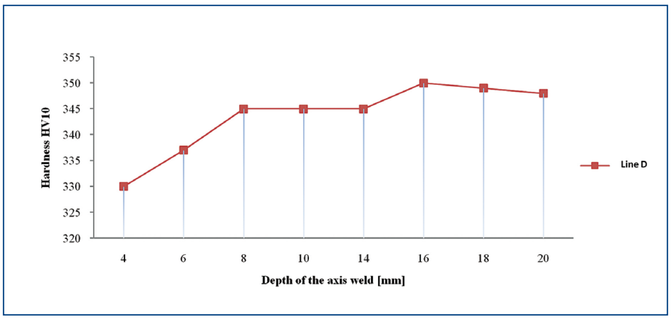

Figure 8. Hardness HV10 in the axis of the weld – line D (TOPOCORE 838 B)

proposed temperature regime during and after welding. It is apparent that when comparing the chemical composition of both filler materials (Tab. 4, 5), it is necessary to point out the higher weight of chromium content in the filler material Thermanit MTS 616 – solid cross-section wire. Thermanit MTS 616 filler material contains 8.8 wt.% chromium, while TOPCORE 838 B filler material – flux-cored wire – contains only 1.1 wt.% chromium. According to the results of mechanical tests [Holub 2014a], it is possible to confirm higher firming of the test sample made with filler material that has higher weight content, where the test bars did not meet the specified ductility in the tensile test and notch toughness in HAZ and WM.

So far has not been found a source that addresses the issue of verification of the mutlilayer-pass work piece numerical calculation on a comprehensive analysis of the resulting internal structures of the resulting residual internal stress and mechanical properties of the base material – 30CrMoNiV5-11 [Holub 2012] [Holub 2013].

7. CONCLUSION

We can conclude that the recommended limit values of HV10 established in accordance with EN ISO 15 614-1 for creep-resistant steel (1.6946) were not exceeded in the test sample welded with TOPCORE 838 B filler material, and that the used welding parameters and thermal processing of Thermanit MTS 616 filler material showed a lower tendency to firming in the heat affected zone and weld metal. Based on these results, it is possible to recommend filler material for welding in the form of TOPCORE 838 B type flux-cored wire.

The transition zone of the weld metal into the base material, where there is a higher risk of precipitation of solid dispersion particles with potential occurrence of hot and cold cracks, was identified as the critical spot in a multilayer weld joint. For a more accurate analysis of the occurrence of brittle zones in heat affected zones, micro analysis of the internal structure of a weld joint with accompanying measurements of (micro) hardness will be conducted in the next phase of research.

Due to high price of the base material and necessity use of the special treatment of the thermal cycles is very suitable to use the numerical computations to simulate the welding process for such applications. The numerical calculations, however, should be thoroughly verified, which is necessary to gain the detailed progressions of mechanical properties and structural changes based on the real experiments. This article shows just the partial evaluation of the progressions hardness´ progressions using different welding consumables.

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