IOP Conference Series: Materials Science and Engineering

Effects of welding on mechanical and microstructural characteristics of high-strength low-alloy steel joints

To cite this article: A Ili *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **393** 012020

IOP Conf. Series: Materials Science and Engineering **393** (2018) 012020 doi:10.1088/1757-899X/393/1/012020

Effects of welding on mechanical and microstructural characteristics of high-strength low-alloy steel joints

A Ilić[1], L Ivanović[1], D Josifović[1], V Lazić[1] and J Živković[1]

[1]University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia

E-mail: andreja.coka@gmail.com

Abstract. In this paper effects of welding on mechanical and microstructural characteristics of high-strength low-alloy steel joints is presented. Testing was done at models prepared with V-groove butt joints that are done by two different welding processes. Considered welding processes were done by MMA or MIG for root pass and MAG for other passes with related consumables. Experimentally determined basic mechanical characteristics were put in correlation to relate ones that were numerically calculated. The experimentally obtained yield strength and tensile strength showed that welding process MMA/MAG provide better mechanical properties then MIG/MAG. It is implicated that selection of welding process at high-strength low-alloy steels is multi criterion analysis. If only proper welding is obtained, applications of high-strength low-alloy steel are adequate. Those applications caused specific problems related to its specific characteristics and properties especially weldability. As welding processes can be analysed from different aspects, selection of specific welding process at high-strength low-alloy steel are more complex.

1. Introduction

Present demands that are related to welded constructions become more complex continuously. On the other side, exploitative and load conditions are more over serious and significant to overall welded construction integrity. Usage of high-strength low-alloyed steels increase, due to its beneficial mechanical properties and by that brings many advantages in design of welded constructions. Adequate forming of joints with related properties and answer to load is critical factor from the aspect of structural integrity and load capacity. Heat input that is unavoidable during welding is most influential factor that cause specific thermic cycles and by that structural transformations. Common welding processes in present industrial practise are based on localized heating, which creates uneven temperature field and by that disrupted expansion and contraction during heating and cooling. Beside thermal stresses, local structural stresses can appear as a consequence of the structural transformations into phases of different specific volumes. These stresses are followed by specific deformations during welding and after this process is finished. Those deformations cause stresses that change character, direction and intensity and represent transitional stresses, while stresses which are permanently present after the welding and the cooling represent residual stresses. Both of those stresses have saviour affect to decrease of properties and characteristics of the welded joint and by that to whole welded construction. High-strength low-alloyed steels fulfil most of the constructional requirements with simultaneous mass reduction, improve energy efficiency, reduced fuel consumption without compromising in reliability, safety and affordability. The light weight capability of those steels resulted from specific microstructure, obtained through of micro-alloying design and highly controlled production processes. Those steels must be considered differently from the conventional steels, which they replaced for general purpose welded constructions. On the other side, characteristics and properties of those steels in exploitation are the result of its microstructure and additional factors. The number and complexity of influential factors in exploitation implicate that mechanical characteristics, properties and answer to load can be determined only by experimental testing under real exploitative conditions. Stress concentration altered the stress distribution, position of maximal stresses and, by that, the position of critical cross section from the aspect of integrity and safety. The numerical simulations of constructions made of high-strength low-alloyed steels are one of the most efficient tool for identification of best design concept of specific welded constructions. But, verification of design concept of welded construction made of high strength steels can only be done relevantly by experimental testing. Presently, welding represents one of the many ways of joining metals. The technology and the procedures of welding are continually developing by application and implementation of the new accomplishments in fundamental scientific disciplines. At this point, identification of most suitable one for actual case appears in relation to factors that are mention above. Selecting of adequate welding procedures with suitable parameters, including, thermal processing of welded joints, when needed, alternation of structural transformations can be reduced to minimum or even can be turned to useful. Identification of welding process and its parameters came in focus of research especially, from the aspect of specific weldability of high-strength low-alloyed steels.

Reference [1] systematically highlights the effect of welding processes and conditions on microstructure, mechanical properties and corrosion resistance of duplex stainless steels and its various combinations on the basis of structure–property co-relationship.

Vukić et al. in reference [2] stated that existing, very scarce and often unclear and insufficient recommendations for selection of the optimal welding technology are one of the causes of large number of flaws in welded joints. It is concluded that mentioned problems, can be successfully solved by proper selection of the procedure, filler metal and technology of welding, verified by experiments conducted in laboratory or in real operating conditions. Thus, partially due to results reported in this paper, technologists will obtain the possibility to predict in advance, in a very short time period, the mechanical and metallurgical properties of joints of this class of high strength steels. This will be possible without conducting the large number of practical tests or relying on personal experience of a designer.

Fydrych with associates in paper [3] characterized problems of high strength steel weldability in underwater wet welding conditions. Water as a welding environment intensifies action of unfavorable factors which influence susceptibility to cold cracking of welded steel joints. The susceptibility to cold cracking of S355J2G3 steel and S500M steel in wet conditions was experimentally estimated. It was concluded that the steels in question are characterized by a high susceptibility to formation of cracks in welds.

Presented short literature overview point out scientific interest and actuality of research presented in this paper. Despite high interest welding of high-strength low-alloyed steels are still not highlighted in details with precise regulations by standards and norms.

2. Experimental testing

The models that are experimentally tested are prepared of high-strength low-alloy steel that correspond to S690QL grade according to EN standard EN 10025-6, steel number 1.8928 classification 3.1/3.2 – EN 10204 / TCM. The used steel is produced by SSAB Oxelösund AB, 613 80 Oxelösund, Sweden with commercial name Weldox 700. Chemical composition of Weldox 700 steel is presented in Table 1. Mechanical properties of used high-strength low-alloy steel Weldox 700 are presented in Table 2.

Table 1. Chemical composition of steel Weldox 700 (S690QL).

Alloying element	Content, %	Alloying element	Content, %
C	max 0.20	V	max 0.09
Si	max 0.60	Cu	max 0.30
Mn	max 1.6	Ti	max 0.04
P	max 0.020	Al	total max 0.015
S	max 0.010	Mo	max 0.70
B	max 0.0005	Ni	max 2.0
Nb	max 0.04	N	max 0.015
Cr	max 0.70		

Table 2. Mechanical properties of steel Weldox 700 (S690QL).

Plate thickness, *mm*	Min. yield strength - Rp0,2, *MPa*	Tensile strength - Rm, *MPa*	Elongation - A, *%*
4,0 - 53,0	700	780-930	14
53,1 - 100,0	650	780-930	14
100,1 - 130,0	630	710-900	14

Butt V-joint is done by welding of 15 *mm* thick plates. For the first group of samples, root pass was done by MMA welding process with welding consumables of lower strength, while other passes were done by MAG welding process with welding consumables of higher strength. For the second group of samples, root pass was done by MIG welding process, while other passes were done by MIG welding process with related welding consumables. Welding parameters for each pass and used welding consumables are presented in Table 3. Quantity of alloying elements in chemical composition and mechanical properties of welding consumables used for welding are presented in Table 4.

Table 3. Parameters used for welding of steel Weldox 700 (S690QL).

Parameter	Root pass MMA	Root pass MIG	Other passes MAG
Welding consumables	INOX B 18/8/6; Ø 3.25 mm	MIG 18/8/6 Si; Ø 1.2 mm	MIG 75; Ø 1.2 mm
Current, Iz	≈ 120 *A*	≈ 110 *A*	≈ 250 *A*
Voltage, U	≈ 24 *V*	≈ 24 *V*	≈ 25 *V*
Welding speed, vz	≈ 0.2 *cm/s*	≈ 0.35 *cm/s*	≈ 0.35 *cm/s*
Heat input, ql	≈ 12 *kJ/cm*	≈ 13 *kJ/cm*	≈ 15 *kJ/cm*
Penetration, δ	≈ 1.8 *mm*	≈ 1.8 *mm*	≈ 1.9 *mm*
Protective atmosphere	-	100% Ar (M11)	82% Ar + 18% CO_2 *(M21)*

Table 4. Chemical composition and mechanical properties of used welding consumables.

Parameter	Root pass MMA	Root pass MIG	Other passes MAG
Chemical composition %			
C	0.12	0.08	0.08
Si	0.8	0.80	0.6
Mn	1.7	7	1.7
Cr	0.19	18.5	0.25
Ni	1.9	9	1.5
Mo	-	-	0.3
Mechanical properties			
R_m, *MPa*	590-690	560 - 660	770-940
$R_{p0.2}$, *MPa*	> 350	> 380	> 690
A_5, *%*	> 40	> 35	> 17
KV, *J*	> 80 (+ 20ºC)	> 40 (+ 20ºC)	> 47 (-40ºC)

Welding was done in real industrial environment by existing equipment in most usual manner. Imperfections and defects are always present in zones of welded joints. Every welding process have one specific potential risks for formation and presence of welding defects. Quality of welded joints is a result of numerous influential factors with complex interactions. Presents of defects and imperfections as result of those parameters come in focus of mechanical construction testing. Welding defects in welded joints are defined and classified in standard EN 26520:1992, while quality of welded joints are defined by EN 25817:1992. Used welding processes were verified and quality of welding joints were checked, defects and imperfections are mention at this point to highlight its importance of welding to overall characteristics of welded construction. Process of welding and appearance of welded joint is presented in Figure 1. Microphotography of cross sections of considered welding joints after metallographic preparation and chemical etching by 4% nitric acid in alcohol are presented in Figure 2.


(a) (b)

Figure 1. Welding process (a) and appearance of welded joint (b).

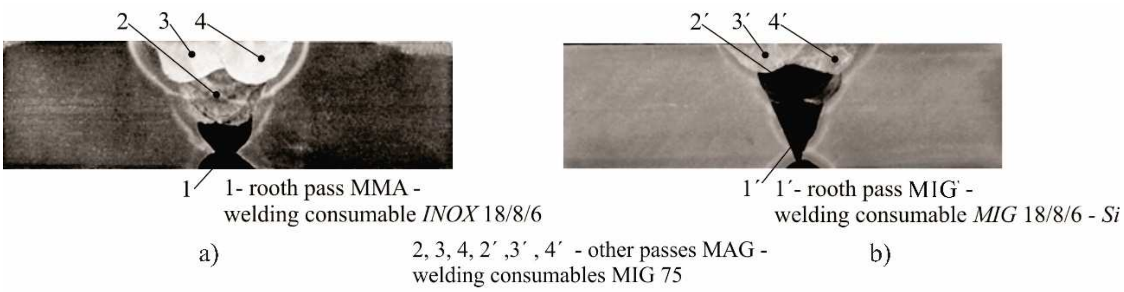


Figure 2. Microphotography of metallurgical samples of welded joints.

Specimens were classified in three series, without welded joint, and other two with considered welded joint types (MMA/MAG and MIG/MAG). Steel plates are cut into pieces, with minimal heat input during cutting with intensive cooling to prepare specimens with welded joint is at the middle of referent zone. Appearance and geometrical characteristics of specimens are presented in Figure 3.

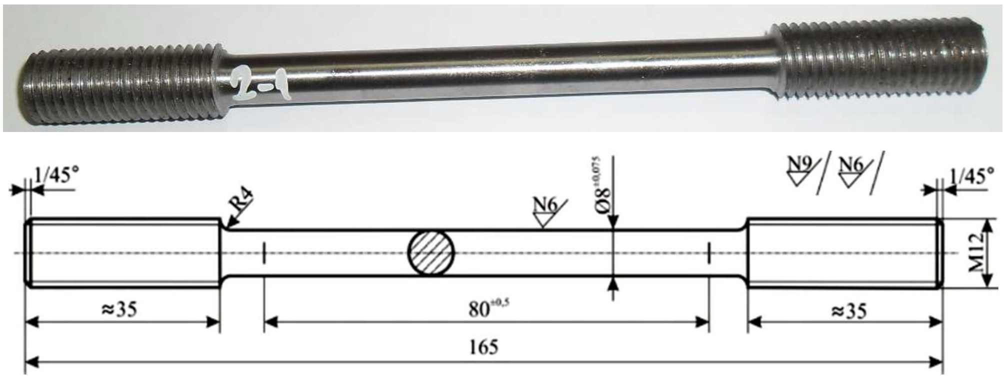


Figure 3. Appearance and geometrical characteristics of specimens.

Determination of mechanical properties at tested specimens ware done. Increase of tension force was adequate for quasi-static testing. Mechanical answer to load of tested specimens has same characteristics. Experimentally determined values of yield strength and tensile strength at tested specimens have insignificant deviations, so experimental results can considered relevant. Dependence of elongation to tension force at tree series of tested specimens are presented in Figure 4.

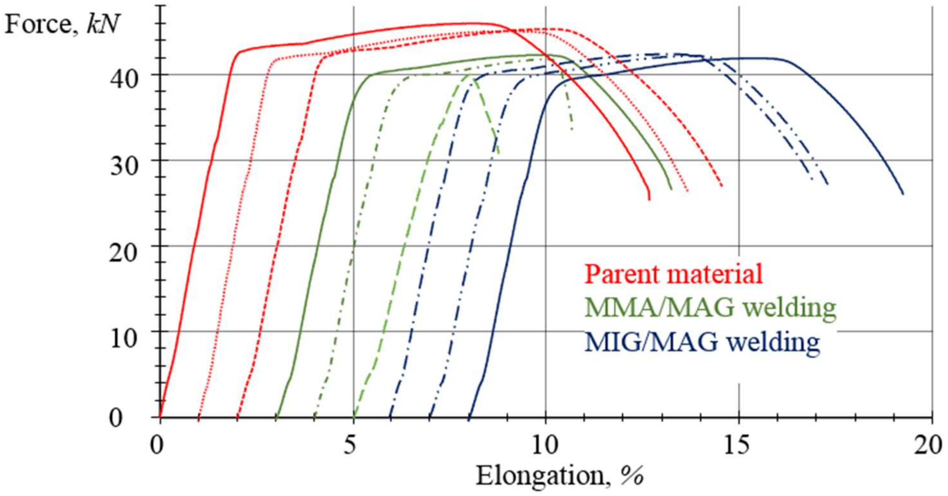


Figure 4. Dependence of elongation to tension force at tree series of specimens.

Experimental testing was done by universal testing device type z100, producer Zwick Roell GmbH & Co. KG at Centre for materials and welding and Laboratory for machine materials and deformation processing, Faculty of engineering in Kragujevac, according to ISO 6892–1:2009 Metallic materials. Tensile testing - Method of test at ambient temperature. During testing, automatic registration of tension force to elongation dependence was done.

Mechanical answer to load at specimens with welded joint during tension to fracture has same characteristics as related at specimens without welded joint. Specific zones at force – elongation dependence can be recognized at specimens with welded joint MMA/MAG and MIG/MAG: zone of linear dependence during elastic deformation, zone of elastic deformation without of linear dependence, zone of plastic deformation, with material yielding at beginning, zone of force increase during plastic deformation to maximal force and fracture zone. Yield strength and tensile strength that are experimentally obtained showed that welding process MMA/MAG provides slightly better mechanical properties then MIG/MAG one. But, MIG/MAG welding process provides higher productivity, possibility of automatizing in present industrial environment. On the basis of the experimentally determined values of yield strength and tensile strength it can be concluded that mechanical properties at specimens with welded joint under static load conditions are within limits of the related values at specimens without welded joint [4].

Fractures occur out of zones of welded joints, so it point out that applied welding processes and parameters are adequate. Also, experimentally determined mechanical properties at specimens with welded joint point out that stress concentration due to welding is minimal under static load condition. Due to properties and characteristics of used high-strength low-alloyed steel, comparison between stresses obtained numerically and experimentally is more interesting.

3. Numerical simulation

Numerical simulation considered in this paper is done by using the software package PAK. The boundary conditions are defined according to theoretical considerations of stress state distributions. The numerical models are loaded with the same level of maximal forces that are obtained experimentally on related models. Visualization of the equivalent plastic strain field for one quarter of model is presented in Figure 5.

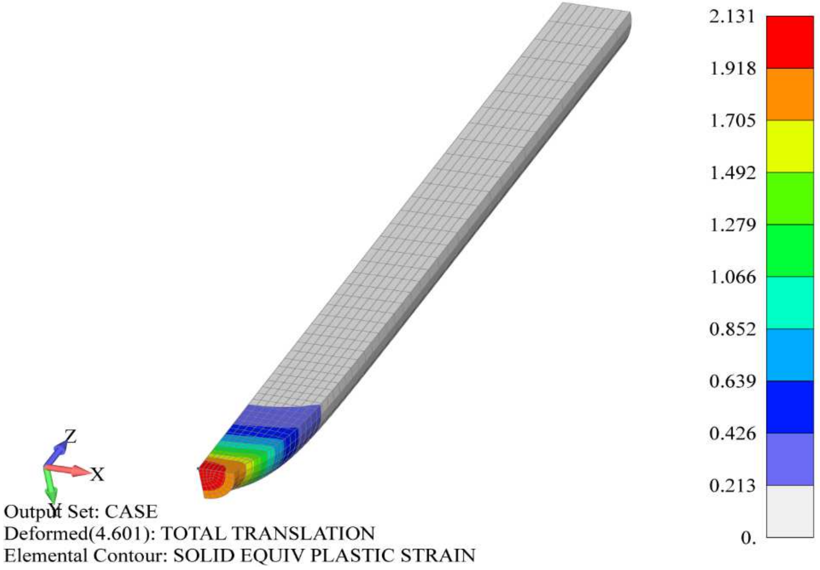


Figure 5. Visualization of the equivalent plastic strain field.

Zone of highest equivalent plastic strain is at fracture zone, while at other zones of considered model equivalent plastic strain is uniform with far less intensity. Numerical simulation is in accordance with theoretical and experimental considerations. Visualization of equivalent stress field

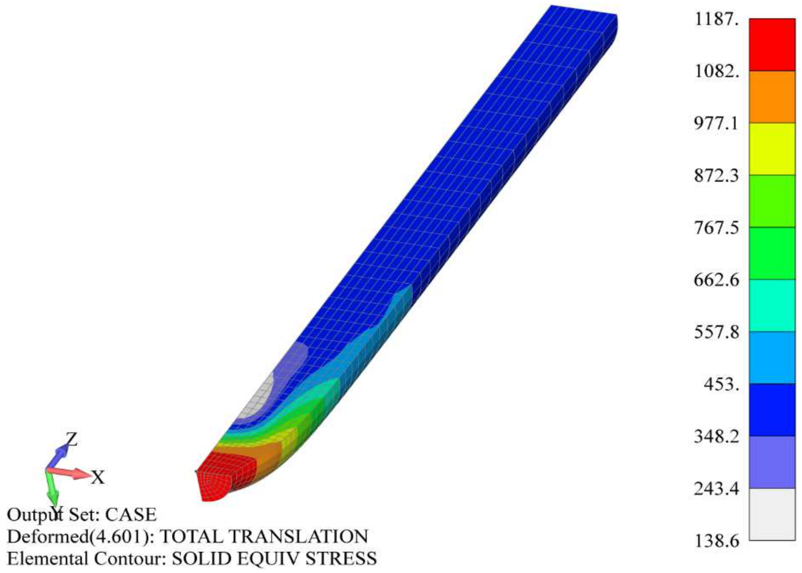


Figure 6. Visualization of the equivalent stress field.

for one quarter of model is presented in Figure 6. Highest equivalent stress act at fracture zone, while stresses at other zones show uniform distribution with far less intensity. Presented facts are in accordance with theoretical and experimental considerations. Dependence of force to elongation during tension to fracture obtained experimentally and numerically is presented in Figure 7.

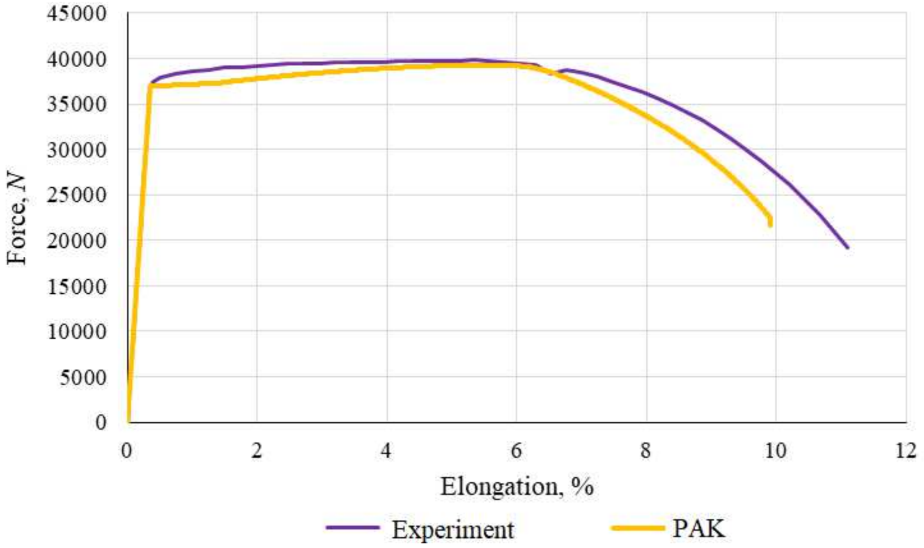


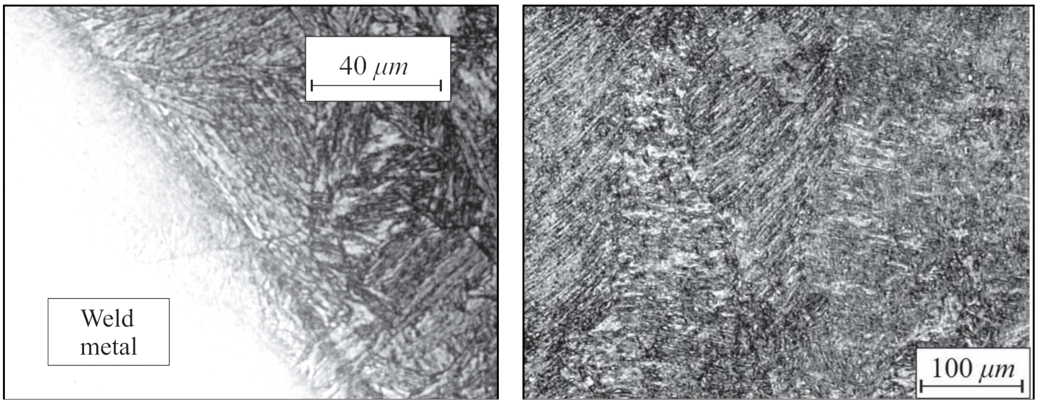
Figure 7. Dependence of force to elongation during tension to fracture obtained experimentally and numerically.

Mechanical answer to load during tension to fracture of experimentally tested specimen and formed mathematical model during numerical simulation have high level of accordance. This point out fact that numerical simulation can be assumed as relevant for analysis of constructions made of high-strength low-alloyed steels. Dependence of force to elongation during tension to fracture obtained by numerical simulations have same characteristic zones as experimentally determined one. Numerical simulations of welded joints zones are more complex and must be based on experimentally determined properties and characteristics of those zones.

4. Stress state and microstructure evaluation at welded joints

The analysis of stress-strain state at the elements of welded constructions is essential factor to whole welded construction integrity. Zones of welded joints by its nature cause multiple stress concentrations, and by that redistributions of stresses. But, those redistributions have local characters, mean value of stresses are different than nominal at those zones, while by small displacements from those zones stresses become equal to nominal very fast. Stress concentrations at welded joints, usually caused increase of stresses, but also, it can relax stress-strain state. It can be concluded that stress concentrations are significant factors that must be taken into account during stress-strain analysis at zones of welded joints. On the basis of the experimentally obtained results it can be concluded that considered welding processes caused comparable stress concentrations. Besides that, zones of welded joints are zones with high level of residual stresses. Residual stresses at zones of welded joints are caused during welding and cooling as consequence of interaction of different phenomena as: obstructed contraction and elongation as result of inhomogeneous distribution of heat during welding, microstructural phase transformations, effects of stress relaxing, etc. Characteristics of residual stresses at weld metal, heat affected zone and surrounding zone depend on high number of complex factors, as transformation temperature and local chemical composition. Also, value of local yield strength that is dependent of temperature and rigidity of construction, is very important. The mechanisms that caused residual stresses are known, but prediction of its values and distribution in certain case is complex due to high number of influential factors and their interactions [5, 6 and 7].

Evaluation of the microstructure state is done by reflex optic micrograph at enlargement of 200 and 500x. Evaluation of the microstructure is done in characteristic zones at metallographic samples, in parent metal, heat-affected zone and weld metal. Microphotography of microstructural states of MMA/MAG samples towards to face of the weld is presented in Figure 8.



(a) (b)

Figure 8. Microstructural states of MMA/MAG samples towards face of weld: (a) zone of transition between weld metal and HAZ; (b) weld metal

The grain bainite microstructure with quenched martensite is registered at the points close to the fusion zones. In the heat affected zones close to the parent metal fine-grain ferrite-pearlite structure with bainite is registered. In weld metal microstructure is assessed as coarse grain bainite with a higher share of martensite. Microstructure states towards face of the welds are similar to the correspondent microstructure of the metallographic sample MMA/MAG weld, implicate that dominant impact of the filling passes. Evaluation of the microstructure is highly in accordance with mechanical characteristics of related welded joint.

5. Results discussions and conclusions

Using of welding consumables with low strength and high plasticity for root pass done by MMA and MIG process provide relaxing of residual stresses. The level of residual stresses at considered welding processes (MMA/MAG and MIG/MAG) is similar.

Processes of microstructural transformations under thermal cycles due to welding are most important factors that cause final microstructure at zone of welded joints. Factors, that influent to final microstructure at zones of welded joints are numerous with complex interactions and are very similar for considered welded processes. Final microstructure is caused, primarily, by welding process that depend on geometry, dimensions, properties and characteristics of joint zone. Local chemical composition resulted from chemical composition of base material and chemical composition of welding consumables, chemical composition of atmosphere, humidity and presents of impurities at welding zone. Welding speed and related heat input due to influence to solidification speed and influence to metal grain growth and segregation are very important to final microstructure.

Thermal cycles of welding due to influence to microstructure of welding zone during and after cooling with chemical composition of weld metal due to influence to precipitation especially at multipass welding technique are also very important [8 and 9].

During welding of high-strength low-alloy steels, cooling speed critical and it is controlled by heat input and preheating procedures at different temperatures. For welding of low thickness elements, cooling speed is also low to provide positive effect to mechanical properties. Austenite welding consumables that are used for root passes of considered welding (MMA and MIG) do not obligatory require preheating. Increase of hardiness at zones of welded joints is consequence of its microstructure and local alteration of chemical composition. Considered welded joins MMA/MAG and MIG/MAG show very similar hardiness increase.

Hydrogen contents are equal for considered welded joints MMA/MAG and MIG/MAG that means that they are not highly susceptible to cracks. At this point it is important to mention that determination of hydrogen equivalent is related to base material. Till now, methodology for determination of hydrogen equivalent related to weld metal is not developed, due to number and complexity of influential factors. Chemical composition of weld metal that is expressed by hydrogen equivalent is essential for susceptibility to cracks [10 and 11].

Welding of high-strength low-alloy steels is more complex process than welding of general purpose constructional steel which they replace. Development steel grades with advanced properties such as high-strength low-alloy steel caused intensive research of welding. High-strength low-alloyed steels due to importance and complexity of its welding usually came with recommend welding technologies and its parameters [12 and 13].

On the other side, weldability is complex characteristic of material related to influence of welding and its parameters in relation to material sensitivity to those processes. Weldability analysis must be done as multi criterion analysis of design solution, selection of material, applied welded process and their mutual interactions. Due to numerous factors, sensitivity of steels, nature of welded joints only experimental testing is fully relevant for verification of welding technology. Analysis of numerical simulation can provide relevant data only if numerical simulation is done on the basis of experimental results and full respect to nature of welded joints zones.

Proper joining by welding is key factor for effective applications of high-strength low-alloyed steels at welded mechanical. But, applications of those steels caused specific problems related to its weldability and providing of required answer to load. Identification of specific welding process of high-strength low-alloyed steel is most important as welding put on numerous different aspects. Development and improving of welding processes must follow present intensive development of high-strength low-alloy steels.

Acknowledgments

Authors wishing to acknowledge support under Serbian Ministry of Education and Science (projects TR 35033 and TR 32036).

References

[1] Jagesvar V and Ravindra V T 2017 Effect of Welding Processes and Conditions on the Microstructure, Mechanical Properties and Corrosion Resistance of Duplex Stainless Steel Weldments – A Review, *Journal of Manufacturing Processes* **25** 134-152

[2] Lazić V, Aleksandrović S, Nikolić R, Prokić R, Cvetković-Popović O, Milosavljević D and Čukić R 2012 Estimates of Weldability and Selection of the Optimal Procedure and Technology for Welding of High Strength Steels, *Procedia Engineering* **40** 310-315

[3] Fydrych D, Labanowski J and Rogalski G 2013 Weldability of High Strength Steels in Wet Welding Conditions, *Polish Maritime Research* **20**(2) 67-73

[4] Ilić A, Ivanović L., Rakić B, Josifović D and Lazić V 2014 *Influence of Welding Technology to Mechanical Properties of Welding Joints at High Strength Low Alloy Steels*, 8th International Symposium on Machine and Industrial Design in Mechanical Engineering KOD, Balatonfüred, Hungary, June 12-15, pp. 255-260

[5] Ilić A 2015 *Influence of Shape Complexity, Material, Stress Concentration and Temperature to Designing of Welded Constructions*, University in Kragujevac, Faculty of Engineering, PhD Thesis

[6] Masuyama F 2017 *Low-Alloyed Steel Grades for Boilers in Ultra-Supercritical Power Plants*, In: Di Gianfrancesco A (Ed.) Materials for Ultra-Supercritical and Advanced Ultra-Supercritical Power Plants, pp. 53-76, Elsevier

[7] Easterling K 2013 *Introduction to the Physical Metallurgy of* Welding, Elsevier

[8] Ilić A, Ivanović L, Josifović D and Lazić V 2012 Design Aspects at Mechanical Constructions Made of High Strength Steel Grades, *Machine design* **4**(3) 131-138

[9] Lezzi F and Costa L 2013 The Development of Conventional Welding Processes in Naval Construction, *Welding International* **27**(10) 786-797

[10] Chen Y X, Yang C D, Wang X J and Chen H B 2015 Evaluation of Metal-Active Gas Double-Sided Double-Power Arc Welded Joints of High-Strength Low-Alloy Steel, *Strength of Materials* **47**(1) 164-169

[11] Brezova E, Masiar H and Radic P 2014 Welding of High Strength Materials Used in the Manufacture Special Equipment, *University Review* **8**(3-4) 51-61

[12] Lazić V, Aleksandrović S, Arsić D, Sedmak A, Ilić A, Djordjević M and Ivanović L 2016 The Influence of Temperature on Mechanical Properties of the Base Material (BM) and Welded Joint (WJ) Made of Steel S690QL, *Metalurgija* **55**(2) 213-216

[13] Stojanović B and Ivanović L 2014 Tribomechanical Systems in Design, *Journal of the Balkan Tribological Association* **20**(1) 25-34