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INFLUENCE OF WELDING TECHNOLOGY TO MECHANICAL PROPERTIES OF WELDING JOINTS AT HIGH STRENGTH LOW ALLOY STEELS

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Abstract: *In this paper the analysis of welding technology to stress-strain state at zones of welded joints at high strength low alloy steel S690QL is presented. Experimental testing was done at specimens with V-groove butt joints that are done by MMA or MIG for root pass and MAG for other passes with related welding consumables. Basic mechanical properties and answer to load of specimens are determined in order to analyses the effect of welding technology to stress-state at zones of welded joints. On the basis of the experimental results it is concluded that welding parameters influent to mechanical properties of joints at high strength low alloy steel S690QL. Those mechanical properties are, primary, related to microstructural transformations caused by thermic cycles due to welding. On the basis of the experimentally obtained results it is concluded that welds with root pass by MIG and other passes by MAG provide better mechanical properties. The general conclusion is that welding parameters at high strength low alloy steels must be selected and controlled with great care in order to obtain welding joints with adequate mechanical properties and, by that, provide beneficial applications of those materials.*

Key words: *high strength low alloy steel, welding joints, stress-strain state*

1. INTRODUCTION

Welded constructions are complex systems of heterogeneous elements whose mechanical properties are highly dependent on stress-state at zones of its welded joints. High strength low alloy steels *S690QL*, due to its beneficial mechanical properties, established during production process, provide many advantages in design of welded constructions. But those steels, are sensitive to heat input that is unavoidable during welding. Structural transformations, which are caused by thermal cycles due to applied welding technologies have major influence to microstructural state at zones of welded joints.

High strength low alloy steels are developed and produced in order to provide beneficial mechanical properties and higher corrosion resistance in relation to conventional structural general purpose carbon steels. Those steels are not classified as alloy steel grades in common manner because their main properties are mechanical, while theirs chemical compositions are of less importance. The processing technology of those steels, altogether with combination of allying elements and their quantities, established beneficial mechanical properties, high corrosion resistance, good deformability and satisfy weldability with minimal level of residual stresses and deformations, suitability to different cutting techniques. This is achieved through highly controlled production processes, special alloy design and high degree of purity with respect to non-metallic inclusions.

The modern demands that are set on welded constructions caused significant increases of applications of those steels. Applications of high strength low alloy steels instead of conventional, general purpose structural steels provide unchanged load capacities with simultaneous reductions in material thicknesses, so as reductions of weight up to 70% averagely. But, significant reductions of thicknesses caused even more complex stress-strain states at elements of those welded constructions. In addition, high strength low alloy steels are sensitive to heat input during welding. All those facts implicate that full understanding of stress-strain state of zones of welded joints is key to successful design of welded constructions and its integrity analysis.

High strength low alloy steels, so as considered *S690QL* (*Weldox 700*) have beneficial mechanical properties, but full benefit of applications of those steels can be obtained only by adequate welding. Using of optimal welding technology is condition of preserving microstructural state and characteristics, that are basis of beneficial mechanical properties, and condition of joining. Literature overview related to welding of high strength low alloyed steels showed that present references are not sufficiently clear and precise.

Willms, in his research, analyzed specific problems related to application of high strength low alloy steel at mechanical constructions [1]. His research point out that application of those steels provide many benefits, but also bring some specific problems. Bjorhovde in his research [2] conclude that high strenght low alloy steels required regulation of design prosedures due to specific characteristics and properties of those steels. Kowieski with associates [3] investigate methodology for selection of welding technology and its properties at high strength steels. Influences of welding processes and parameters to microstructure and mechanical properties of welded joints at high strength low alloy steels are investigated by Shi [4]. Moon and associates [5] investigate processes that are caused during welding at high strength low alloy steels and its influences to characteristics and mechanical properties of welded joints. The presented references consider welded construction ether as one entity or at microstructural level. The research presented in this paper consider welded construction by analysis of mechanical properties at models related to real zones of welded joints. Applied research methodology provide results that are practical for using during design processes of welded constructions.

2. EXPERIMENTAL TESTING, MODELS AND METHOD

For preparation of specimens that are experimentally tested, high strength low alloy steels, commercially nominated as *Weldox 700*, is used. The used steel is produced by SSAB Oxelösund AB, 613 80 Oxelösund, Sweden and fulfill requirement classified for *EN 10025-6:2004* nomination *S690* [7]. Chemical composition of *Weldox 700* steel, according to data provide by producer is presented at Table 1.

Table 1. Chemical composition of Weldox 700 steel

Chemical element	Content, %	Chemical 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 0,010
Cr	max 0,07		

Mechanical properties of considered high strength low alloy steel *Weldox 700* in relation to plate thickness according to producer SSAB Oxelösund AB are presented at Table 2.

Table 2. Mechanical properties of Weldox 700 steel

Plate thickness, *mm*	Min. yield strength - $R_{p0,2}$, *MPa*	Tensile strength - R_m, *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

High strength low alloy steel Weldox 700 is produced in two grades, nominated with suffix *E* and *F* in dependence to impact toughness. Values of impact energy for *Weldox 700* steel determined at *V*-notch Sharpy specimens (*EN ISO 148-1:2010* and *EN 10045-1:1990*) are presented at Table 3 [8 and 9].

Table 3. Impact energy of Weldox 700 steel

	Weldox 700E at -40°C	*Weldox 700F* at -60°C
Min. impact energy	69 J	27 J
Nomenclature according to *EN 10025-6:2004*	S690QL	S690QL1

High strength low alloy steels have conditional weldability. This condition is related to additional procedures that provide required characteristic of joining by welding. But, welding of those steels caused degradation of its microstructural state and characteristics, especially at heat affected zones of welding joints. The processes of degradation can be related to: increase of hardness, decrease of toughness, increase of transition temperature, presence of different material discontinuities and so on. Initialization of cracks and brittle structures due to welding are related to high cooling speed of weld metal and its surrounding zone in diapason of temperature in which austenite is highly unstable.

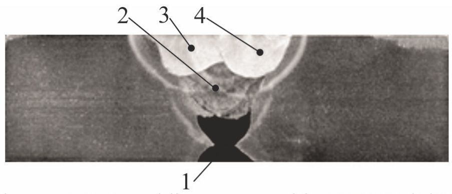
Analysis of mechanical properties of high strength low alloy steels must be based on its specific characteristics:

- Limited plasticity reserve due to high strength of steels,
- Possibility of local zone with lower plasticity in relation to rest of the construction and
- Possibility of initialization of cracks (primarily, hydrogen) during welding at weld metal and heat affected zone. Those cracks are potential stress concentrators and causes of brittle fracture.

During welding of high strength low alloy steel preference is given to welding processes with lower energy, such as MMA and welding at protective atmosphere of gasses that are considered in this paper. Welding technology and parameters are selected in correlation to used material, thickens and recommendations. The best mechanical properties and low levels of residual stresses and deformations are obtained by using of welding consumables with lower strength and high plasticity for root pass, and higher strength for other passes, at multipass welding techniques. The root pass of those multipass welding techniques can be done by different welding processes. Every one of those welding processes have own specific influence to mechanical properties and characteristics of welding joints that are in focus of this paper. Also, every welding process have its own specific characteristics, from the aspect of economy, welding speed, possibility of automatizing, availability at specific industrial environment, and so on. Those facts, besides of welding joints properties, present very significant factors that influent to selection of welding process at high strength low alloy steels.

Butt *V*-joint is done by welding at plates with thickness of 15 *mm*. Microphotography of cross sections of considered welding joints after metallographic preparation and chemical etching by 4% nitric acid in alcohol are presented at Fig. 1. In first case (Fig. 1a)), root pass is done by MMA welding process and welding consumables with lower strength (pass - 1), while other passes are done by MAG welding process and welding consumables with higher strength (passes - 2, 3 and 4). In second case (Fig. 1b), root pass is done by MIG welding process (pass - 1´), while other passes are done by MIG welding process and related welding consumables (passes - 2´, 3´ and 4´). The welding was done after preparation of *V*-groves with defined geometry and dimensions for every welding technique. The welding was done at real industrial environment with using of existing equipment.

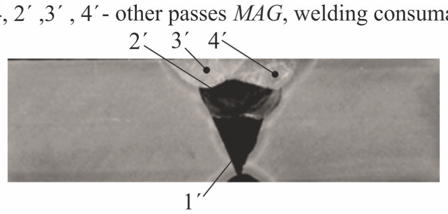
a)



1- rooth pass *MMA*, welding consumable *INOX* 18/8/6

2, 3, 4, 2´ ,3´ , 4´- other passes *MAG*, welding consumables *MIG 75*

b)



1´- rooth pass *MIG*, welding consumable *MIG* 18/8/6 - *Si*

Fig.1. Microphotography of cross-sections of considered welded joints

Chemical compositions and mechanical properties of welding consumables that are used are presented at Table 4.

Table 4. Chemical compositions and mechanical properties of welding consumables

		INOX B18/8/6	*MIG* 18/8/6 *Si*	*MIG* 75
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 (+ 20℃)	> 40 (+ 20℃)	> 47 (-40℃)

Welding parameters for each pass of multipass welding technique and related welding consumables are presented at Table 5.

Table 5. Welding parameters

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, I_z	≈ 120 *A*	≈ 110 *A*	≈ 250 *A*
Voltage, *U*	≈ 24 *V*	≈ 24 *V*	≈ 25 *V*
Welding speed, v_z	≈ 0.2 *cm/s*	≈ 0.35 *cm/s*	≈ 0.35 *cm/s*
Heat input, q_l	≈ 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*)

After welding, plates are cut into pieces, with minimal heat input during cutting, according to cutting scheme. After mechanical processing, with intensive cooling, specimens are made (Fig. 2).

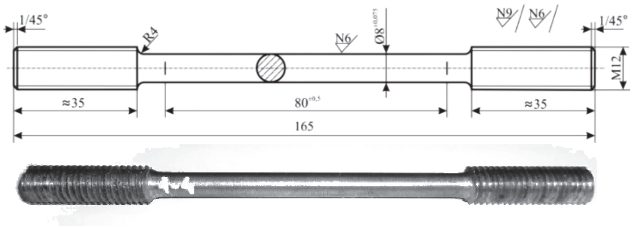


Fig.2. Shape and dimensions of specimens

Specimens are made and classified in three series, one without welded joint, and other two with considered welded joint MMA/MAG and MIG/MAG. Welded joint is at the middle of referent zone of specimen. Experimental testing are done at Center for materials and welding and Laboratory for machine materials and deformation processing, Faculty of engineering in Kragujevac, Serbia according to regulation ISO 6892–1:2009 Metallic materials. Tensile testing. Method of test at ambient temperature [10]. Experimental testing of mechanical properties are done at ambient temperature by universal testing device type z100, producer Zwick Roell GmbH & Co. KG (Fig. 3).

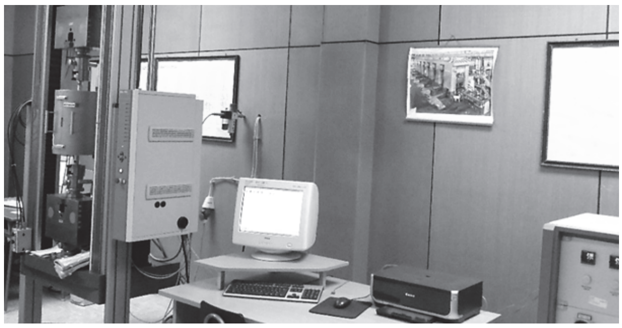


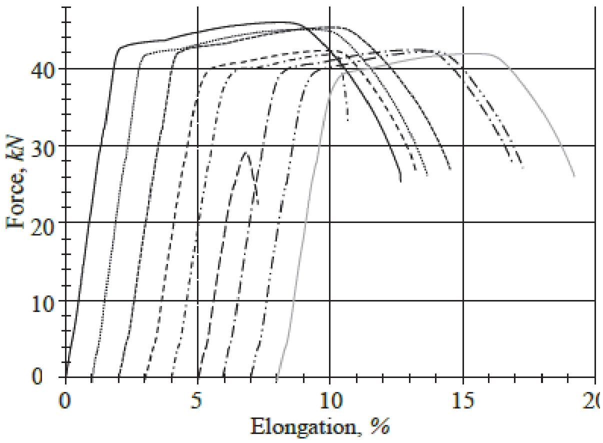
Fig.3. Universal testing device Zwick Roell z100

Maximal load force of the used testing device if 100 *kN*, speed of moving support is in range of 0.0005 to 750 *mm/min*. Measuring of force in range of 0.4 to 100% of nominal force is adequate for Class 1 measuring devices. Initial length of extensometer is 11 to 50 *mm*. Position resolution of moving support of the device is 0.0207 *μм* [11].

Testing methodology enclose preparation and set up of specimens at testing device, loading to fracture in quasi-static conditions at ambient temperature. Automatic registration of dependence tension force -elongation and determination of basic mechanical properties at tested specimens ware done during testing. Speed of force increase during testing was adequate for quasi-static testing.

Experimentally determined values of yield strength and tensile strength at tested specimens have insignificant deviations and mechanical answer to load have same characteristics, so results can be taken as relevant.

Experimentally determined dependence tension force - elongation at tested specimens are presented at Fig.4.



	Mark / Type		Mark / Type		Mark / Type
	1.1 BM		2.1 MMA/MAG		3.1 MIG/MAG
	1.2 BM		2.2 MMA/MAG		3.2 MIG/MAG
	1.3 BM		2.3 MMA/MAG		3.3 MIG/MAG

Fig.4. Dependence force - elongation at tested specimen

Experimentally determined yield strength $R_{p0,2}$=739.59 *MPa* and tensile strength R_m=796.66 *MPa* at tested specimens made of considered material fulfill requirements defined by EN and national norms for high strength low alloy steel *S690QL* and overcome values stated by producer. Elongation to fracture determined by experimental testing of $A_{11,3}$=11*%* is within defined range for considered material. At specimen, mark with 2-3 MMA/MAG, fracture happened at significantly low tensile force, as consequence of defect during welding, so this specimen is excluded from further considerations. Welding defects occur during all welding processes and every process have own specific possibility of defects.

Quality of welded joints depend on great number of factors, but presence of defects must be in focus during forming and exploitation of welded mechanical constructions. Welding defects are defined and categorized by norm *EN 26520:1992* - Classification of imperfections in metallic fusion welds and quality of welding is defined by norm *EN 25817:1992* - Arc-welded joints in steel. Guidance on quality levels for imperfections [12 and 13]. As applied welded processes are verified and quality of considered welded joint are adequate, defect at specimen 2-3 REL/MAG is presented in order to highlight importance of influence of welding defects and imperfections to mechanical properties of joints. Experimentally determined yield strength and tensile strength at tested specimens that is presented at Fig. 4 by histograms, 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.

Comparison of experimentally determined yield strength and tensile strength at tested specimens is presented at Fig.5.

Positions of fractures out of zones of welded joints at tested specimens point out that applied welding processes and parameters are adequate.

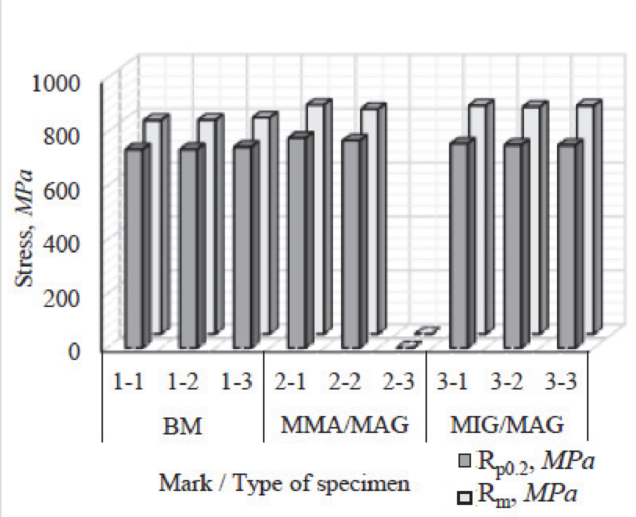


Fig.5 Yield strength and tensile strength at tested specimens

Also, experimentally determined mechanical properties at specimens with welded joint point out that stress concentration due to welded joint is minimal under static load condition and at ambient temperature. Mechanical answer to load at specimens with welded joint during tension to fracture, means force – elongation dependence, have same characteristics as related at specimens without welded joint. Specific zones can be recognized during analysis of tensile force – elongation dependence at specimens with considered type of 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. The experimentally obtained yield strength and tensile strength showed that welding process MMA/MAG provide slightly better mechanical properties then MIG/MAG. But, MIG/MAG welding process provide higher productivity, possibility of automatizing in real industrial environment. Those fact also point out that selection of welding process at high strength low alloy steels is multi criterion analysis.

3. STERESS-STRAIN STATE AT WELDED JOINTS

The analysis of stress-strain state at the elements of welded constructions by theoretical and experimental methods showed that actual stresses are significantly different from nominal stresses at zones of discontinuities such as welding zones. Zones of welded joints by its nature, so as by conditional material discontinuity caused 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 at zones of welded joints. Presented facts lead to conclusion that stress concentrations are significant factors that must be taken into account during stress-strain analysis at zones of welded joints [14]. Experimentally obtained results showed that both considered welding processes MMA/MAG and MIG/MAG caused very similar stress concentration. On the other hand, zones of welded joints are zones with high level of residual stresses. Residual stresses at zones of welded joints as consequence of interaction of different phenomena that are caused during welding, such as: obstructed contraction and elongation as result of inhomogeneous distribution of heat during welding, microstructural phase transformations, effects of stress relaxing. Characteristics of residual stresses at weld metal, heat affected zone and surrounding zone depend on high number of complex factors, as transformation temperature and highly important, local chemical composition. Also, value of local yield strength that is dependent of temperature and rigidity of construction, is very important. The basic mechanisms that caused residual stresses at welded mechanical constructions are known, but prediction of its values and distribution in certain case is very complex due to relatively high number of influential factors and its interactions. The level of residual stresses at both considered welding processes MMA/MAG and MIG/MAG are equal. Welding consumables for root pass done by MMA and MIG process with low strength and high plasticity provide relaxing of residual stresses.

Solidification processes, mean processes of microstructural transformations under thermal cycles due to welding are most important factor that influent to final microstructure of material at zone of welded joints. Factors, that influent to final microstructure of material at zones of welded joints are numerous with complex interactions. Those factors are very similar for both of considered welded processes MMA/MAG and MIG/MAG and can be classified as:

- Welding process that depend on geometry, dimensions, properties and characteristics of joint zone,
- Local chemical composition that 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,
- Thermal cycles of welding due to influence to microstructure of welding zone during and after cooling and
- Chemical composition of weld metal due to influence to precipitation especially at multipass welding technique.

During welding at high strength low alloy steels, cooling speed is controlled by control of heat input and preheating procedures at different temperatures. During welding of elements with low thickness, cooling speed is also low that have positive effect to mechanical properties. When austenite welding consumables are used, preheating is not obligation, as those welding consumables that are used for root passes of considered welding joints done by MMA and MIG process. Increase of hardness at zones of welded joints is direct consequence of its microstructure and chemical composition. Considered welded joins MMA/MAG and MIG/MAG have very similar increase of hardness. Formulas for determination of hydrogen equivalent are related to base material, and till now those formulas are not developed for weld metal due to number and complexity of influential factors. Chemical composition of weld metal, expressed by hydrogen equivalent is essential for susceptibility to cracks. Considered welded joints MMA/MAG and MIG/MAG have equal hydrogen content and are not highly susceptible to cracks.

4. CONCLUSION

Joining by welding, especially at high strength low alloy steels is complex process with high number of influential factors. Development of advanced generation of steels as high strength low alloy steel caused intensive research of its welding processes. Producers of high strength low alloy steels due to importance and complexity of welding and sensitivity of those steels to welding also recommend welding technologies and its parameters.

Weldability is complex characteristic of material that is related to influence of welding process and its parameters to welded joint, its characteristics and mechanical answer to load from stress-strain aspect. But, real evaluation of weldability must be done as analysis of design solution, selection of material, applied welded process and their interactions, as it is presented illustratively at Fig.6.

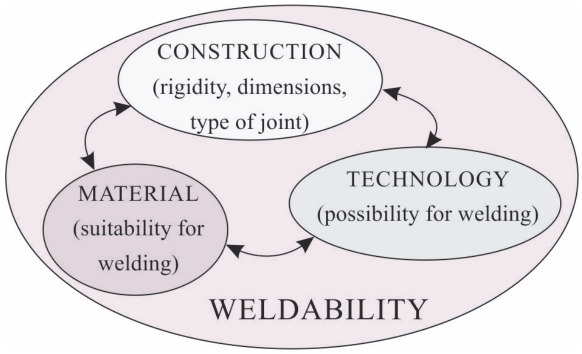


Fig.6. Weldability as complex phenomena

Experimental testing of specimens with related similarity to zones of welded joints combine presented factors in general and provide analysis of mechanical properties at real exploitative conditions. Also, only experimental testing is fully relevant for verification on applied welding technology.

Applications of high strength low alloy steel at welded mechanical constructions are adequate only if proper joining by welding is obtained [15, 16 and 17]. Also, those applications caused specific problems related to its weldability and providing of required quality. Besides that, as welding processes can be analysed from different aspects, selection of specific welding process at high strength low alloy steel is very important. Intensive development of high strength low alloy steels must be followed by development and improving of welding processes and techniques.

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