Welding method as influential factor of mechanical properties at high-strength low-alloyed steels

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Abstract. In this paper the analysis of welding technology to mechanical properties of welded joints at high strength low alloyed steel S690QL is presented. Experimental testing was done at models with V-groove butt joints that are done by MMA or MIG for root pass and MAG for other passes of multipass welded joints with related parameters and consumables. Yield and tensile strength, so as answer to load of models are determined experimentally in order to analyses the effect of welding technology to resulted mechanical properties. On the basis of the obtained results it can be concluded that welding parameters have significant influence to mechanical properties of welded joints at high-strength low-alloyed steel. Furthermore, it can be concluded that welded joints with root pass done by MIG and other passes by MAG provide better mechanical properties. Presented research point out that welding parameters at high strength low alloyed steels must be selected and controlled precisely to obtain welding joints with adequate mechanical properties. Welding, as dominant method of joining, is primary factor that provide beneficial application of high-strength low-alloyed steels. The paper highlight the influence of material degradation due to welding. This paper point out the importance of analysing the welded joints at different levels of dimensions, while further, more detailed, research can be continued through development of a numerical model of the welded joints which will complete the experimentally obtained results. As experimentally obtained results correlate to material degradation due to welding it is implicated that future development of high-strength low-alloyed steels must be followed with development and modification of welding processes.

1. Introduction

High-strength steels were developed in order to improve the mechanical characteristics and corrosion resistance of conventional carbon steels during seventh decade of the 20th century and linked to the beginnings of commercial production of iron alloys, especially ferroniobium. The typical microstructures of high-strength low-alloy steels are fine grain, consist of small size ferrite (α) grains with shape homogeneity. The small quantity of cementite is also present in microstructures, so as the fine dispersed particles of carbon nitride (can be identify only by using of electron microscope). During the final rolling process advantageous conditions for creation of the large number of referent locations within the discrete formation of α metal grains. The density of those locations is a consequence of a production processes and material deformation. The effects of regeneration of deformed microstructure are induces, as recuperation and recristalization. By those phenomena, the deformed microstructure goes into the undeformed form means decrease of dislocation density in the microstructure. The recristalization processes are blocked by decrease of speeds of grains' nucleus formation and by the reduction of movement of metal grains and sub grains boundaries. The recristalization processes are caused by the presence of alloying elements' in the solid solution and
induced by continual rolling with small pause periods, when dominant is the effect of niobium. The recrystalization processes are made as the consequence of precipitation during the reversible rolling with longer pause periods, when the separation of carbon nitride is dominant process.

Welding procedures are developing by the intensive applications of the obtained results in fundamental and applied scientific disciplines. Common welding process is based on localized heating and, after that, cooling, means inhomogeneous temperature fields at heat affected zones of welded joints. Present welding technology processes bring numerous and heterogeneous consequences by its nature, as inhomogeneity of material, alteration of chemical compositions, microstructural transformations, etc. Material degradation of high-strength low-alloyed steels due to welding can be related to increasing of hardness and transition temperature, a decrease of toughness, different material discontinuities and etc. Formation of brittle structures and initialization of cracks due to welding are related to the high cooling speed of weld zone in diapason of temperature at which austenite is highly unstable.

Material discontinues (inclusions, defects, cracks, sharp cuts, etc.) and imperfections often exist at welded joint zones means that they are critical from the aspect of structural integrity. Also, from the same aspect, safety and reliability analysis, construction answer to load is crucial. The welded construction answer to load and its ability to absorb energy with preserved integrity come in focus of many researches.

Reference [1] presents a comparative analysis between the mechanical properties of high strength steel weld metals obtained by shielded metal arc (SMAW) and gas metal arc (GMAW) welding processes. Multipass welding by SMAW and GMAW processes was performed with preheating of 200 °C in plates. After welding, a post weld heat treatment (PWHT) at 600 °C for 1 h was performed and this condition was compared to the as welded one. Mechanical tests and metallographic examination by optical microscopy (OM), scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) were performed for mechanical and microstructural characterization. It is concluded in this reference that presenting impact toughness behaviour slightly different due to the chemical composition and carbide precipitates, as predicted by computational simulation, both processes showed a good relationship between mechanical strength and impact toughness for all analysed conditions, even after PWHT. It can be concluded that GMAW process can be applied as an interesting alternative for welding of high strength steels, once this process promotes a significant improvement in productivity with good quality.

Nathan with associates in reference [2] present that naval grade high-strength low-alloy (HSLA) steels can be easily welded by all types of fusion welding processes. Fusion welding of these steels leads to the problems such as cold cracking, residual stress, distortion and fatigue damage. It is concluded that these problems can be eliminated by solid state welding process such as friction stir welding (FSW). The reference [2] present comparative evaluation of mechanical (tensile, impact, hardness) properties and microstructural features of shielded metal arc (SMA), gas metal arc (GMA) and friction stir welded (FSW) naval grade HSLA steel joints. It is concluded that the use of FSW process eliminated the problems related to fusion welding processes and also resulted in the superior mechanical properties compared to GMA and SMA welded joints.

Reference [3] presents the analysis of the weldability of three different modern high strength steel plates, with a thickness of 8 mm. Two of the test materials were produced by a thermo-mechanically controlled process (TMCP) and one by a quenching and tempering method (Q&T). Two-passes MAG (metal active gas) welding was used with four different heat inputs. The tests implemented on all the materials included tensile, hardness profiles (HV5), Charpy-V impact toughness tests, and microstructure analysis using scanning electron microscope (SEM). For one of the TMCP steels, some extended tests were conducted to define how the tensile properties change along the weld line. These tests included tensile tests with digital image correlation (DIC), and 3-point bending tests. The most notable differences in mechanical properties of the welds between the materials were observed in Charpy-V impact toughness tests, mostly at the vicinity of the fusion line, with the Q&T steel more prone to embrittlement of the heat affected zone (HAZ) than the TMCP steels. Microstructural analysis revealed carbide concentration combined with coarse bainitic structures in HAZ of Q&T steel, explaining the more severe embrittlement. During the tensile tests, the DIC measurements have
shown a strain localization in the softest region of the HAZ. Increasing the heat input resulted in earlier localization of the strain and less maximum strength. The tensile properties along the weld line were investigated in all welding conditions, and the results emphasize relevant and systematic differences of the yield strength at the transient zones near the start and end of the weld compared with the intermediate stationary domain.

Zgripcea with associates in reference [4] presents application domains of high strength weld, fabrication technologies and tests. High strength weld is used for assembly of high strength low alloyed steel (HSLA) where the same or greater mechanical properties must be obtained in weld line. The method presented in this paper is based on micro alloying inside the root of the weld, with minimum supplementary cost and keeping the same productivity for welding process. The applications of this method are realizations of storage pressure vessels, shields, crane arms and generally, all applications where high strength at a low weight are required.

The presented literature overview point out that properties and characteristics of welded joints are crucial element of structural integrity of the whole welded constructions. Welded constructions are complex systems that can be considered from many different aspects. Safety and reliability analysis of welded constructions also point out that welded joints are critical zones.

The aim of determining answer to load and mechanical properties of welded joints is the qualitative analysis of structural integrity due to the integrity of its welded joints. Capacity calculations analyse and prove mechanical response and integrity of welded structures for the anticipated loads and exploitative conditions. The most dominant factors to relevance of analytical models used for calculations are stress concentrations at zones of welded joints. Exploitation of welded constructions showed that properties of welded joints, due to theirs nature, were not adequately take in consideration in present analytical models, so as capacity calculations. It can be concluded that only results obtained by experimental testing can be taken as highly relevant.

2. Experimental testing of welded joints
The experimentally tested models are made of high-strength low-alloy steel that related to EN standard EN 10025-6, steel number 1.8928 classification 3.1/3.2 – EN 10204 / TCM, commercially Weldox 700 - S690QL. The analysed steel is produced by SSAB Oxelösund AB, 613 80 Oxelösund, Sweden. Chemical composition of alloying elements is presented in table 1.

| 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  |                  |           |

The considered high steel grade are developed to provide the favourable mechanical properties and higher corrosion resistance and not classified as alloyed steel grades in common manner. Those steels contain small amounts of nickel, molybdenum, copper, nitrogen, vanadium, niobium, titan, zirconium and boron. Combination of alloying elements and their quantities provide the proper weldability and deformability are obtained. Also, this is achieved through highly controlled production processes and a high degree of purity with respect to non-metallic inclusions. The nature of microstructure of high-strength steels, so as theirs characteristics must be considered adequately in design process. The microstructure of considered high-strength low-alloyed steel is fine grained and consist of fine ferrite
(α) grains with uniformity of shapes. The small amounts of cementite is present in microstructures and fine dispersed particles of carbon nitride (figure 1) [5, 6, 7].

Figure 1. Typical microstructure of high-strength low-alloyed steels.

Two different groups of samples with butt V-joint are prepared 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 [5, 6, 7]. Welding parameters and used filler material are presented in Table 2.

Table 2. Parameters and filler material used for welding.

| 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% CO₂ (M21) |

Welding of plates and reparation of samples was done in industrial environment. Presence of imperfections and defects in zones of welded joints is inevitable. Potential risks for formation and presence of welding defects are related to every specific welding process. 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 before experimental testing. Testing was done Experimental testing are done at ambient temperature by universal testing device type z100 producer Zwick Roell GmbH & Co. KG according to regulation ISO 6892–1:2009 Metallic materials. Tensile testing. Method of test at ambient temperature (figure 2).
Testing methodology involve loading to fracture in quasi-static conditions at ambient temperature with automatic registration of dependence tension force-elongation and determination of basic mechanical properties. Speed of force increase was suitable for quasi-static testing [5, 6, 7].

Specimens were tested in series, made of parent metal without welded joint, and other two with considered welded joint types. 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.

Location of the fractures surfaces at tested specimens are out of zones of welded joins and by that point out that applied welding processes are done adequately. Mechanical answer to load of the specimens with and without welded joint during tension to fracture have same related characteristics. Specific zones can be accepted during tension to fracture at specimens with welded joint MMA/MAG or 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. Comparison of experimentally determined yield and tensile strength of the tested specimens is presented at figure 4.
Figure 4. Histograms of yield and tensile strength of tested specimens.

Experimentally determined values of yield strength and tensile strength at tested specimens have insignificant deviations so results can be taken as relevant. Experimentally determined yield strength $Rp_{0.2}=739.59$ MPa and tensile strength $Rm=796.66$ MPa at tested specimens made of considered material fulfill requirements defined by norm for considered high-strength low-alloy steel. Experimentally determined elongation to fracture is within range for considered material. At one specimen with MMA/MAG joint fracture happened at significantly low tensile force, as consequence of defect during welding, so this specimen is excluded from further evaluation. Presented facts verifies significance of welding defects. The experimentally obtained yield strength and tensile strength showed that MMA/MAG welding process provide better mechanical properties then MIG/MAG. But, MIG/MAG welding process provide higher productivity, possibility of automatization in present industrial environment. Those fact also point out that selection of welding process at high strength low alloy steels is multi criterion analysis [5, 6, 7].

3. Results evaluation and discussion

Characteristic and properties of welded joints depend on excessive number of factors. Presence of defects must be considered in details during forming and exploitation of welded 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.

Zones of welded joints by nature as zones of conditional material discontinuity caused multiple stress concentrations. Redistributions of stresses have local characters. Stress concentrations at welded joints, usually caused increase of stresses, but it can also relax stress-strain state [8, 9, 10]. Experimentally obtained results of mechanical properties showed that both considered MMA/MAG and MIG/MAG welding caused comparable stress concentration.

Residual stresses at zones of welded joints are consequence of interaction of different phenomena caused by welding. Characteristics of residual stresses at weld metal, heat affected zone and surrounding zone depend on number of complex factors. The basic mechanisms that caused residual stresses at welded mechanical constructions are identified, but estimate of values and distribution is very complex. Mechanical answer to load and values of yield and tensile strength of tested specimens showed that level of residual stresses at considered welding processes are equal [11, 12, 13]. 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.

Joining by welding at high-strength low-alloy steels is complex process with large number of influential factors. Producers of high-strength low-alloy steels due to importance and complexity of welding and sensitivity of those steels to welding also recommend welding processes and parameters.

Weldability is complex characteristic of material that is related to influence of welding process and its parameters to characteristics and properties of welded joint. Presented facts lead to conclusion that overall characteristics and mechanical answer to load from stress-strain aspect are highly influenced by welding. Evaluation of weldability in details must be done as analysis of design solution, selection of material, applied welded process and their interactions [14, 15, 16, 17].

4. Conclusion

Present norms and standards of welding joints design at high-strength low-alloy steels are based on heterogeneous backgrounds. Limitations are established during design process from different reasons in order to provide welded joint with adequate mechanical properties. Improving resistance of welding joints to forming of defect and inclusions are based on relaxing residual stresses, reducing hydrogen content and obtaining preferred thermal cycles. Present standards and recommendations are not still fully developed and precise. Effects of specific welding parameters to microstructural state at different zones of welding joins are not analysed in details. Distribution of microhardness and mechanical properties of the joint as complex characteristic are caused by large number of factors. Those relations are in focus of research presented in this paper on qualitative level. From the practical aspect, mechanical characteristics and properties of welded joints at this steel grade is crucial.

High-strength low-alloy steels welding is far more complex than welding of other general purpose constructional steel grades. Development of steel grades with advanced properties such as high-strength low-alloy steel caused intensive research of its welding. High-strength low-alloyed steels due to importance and complexity of its welding usually came with recommend welding technologies and its parameters. Weldability is complex characteristic of material related to influence of welding and its parameters in relation to material sensitivity. Weldability analysis must be done as multi criterion analysis of design solution, selection of material, applied welded process and their mutual interactions.

Present demand related to welded constructions become far more complex. Simultaneously, exploitative and load conditions are more serious and much more significant to construction answer to load and its integrity. Welded constructions are complex systems of heterogeneous elements with mechanical properties that are highly influenced by its welded joints.

High-strength low-alloy steels due to specific microstructure and alloying design are sensitive to welding influences, but applications of those steels instead of conventional, general purpose structural steels provide many advantages. It can be concluded that full benefit of applications of those steels can be obtained only by suitable welding. Appropriate welding is the main condition for preserving material characteristics and properties means minimalizing of its degradation, that are the basis of proper mechanical properties, and condition of joining. Share of usage of high-strength low-alloyed steels continually increase and forming of joints is critical factor from the aspect of structural integrity and load capacity. Mechanical properties of high-strength low-alloy steels are highly influenced by its specific characteristics, as limited plasticity reserve due to high strength of steels, possible formation of local zones with lower plasticity in relation to rest of the construction and possibility of material discontinuities and initialization of cracks (primarily, hydrogen) during welding at weld metal and heat affected zone.

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