Mechanical Properties of Heat Affected Zone of High Strength Steels

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Abstract. High Strength Steels became more popular as a construction material during last decade because of their increased availability and affordability. On the other hand, even though general use of Advanced High Strength Steels (AHSS) is expanding, the wide utilization is limited because of insufficient information about their behaviour in structures. The most widely used technique for joining steels is fusion welding. The welding process has an influence not only on the welded connection but on the area near this connection, the so-called heat affected zone, as well. For that reason it is very important to be able to determine the properties in the heat affected zone (HAZ). This area of investigation is being continuously developed in dependence on significant progress in material production, especially regarding new types of steels available. There are currently several types of AHSS on the world market. Two most widely used processes for AHSS production are Thermo-Mechanically Controlled Processing (TMCP) and Quenching in connection with Tempering. In the presented study, TMCP and QC steels grade S960 were investigated. The study is focused on the changes of strength, ductility, hardness and impact strength in heat affected zone based on the used amount of heat input.

1. Introduction

1.1. General

The research of welded connections of high strength steel started at Czech Technical University in Prague in cooperation with Kemi-Tornio University of Applied Sciences in 2012. The first research work was focused on using and evaluation of advanced techniques for the investigation of behaviour...
of high strength steel [1]. These techniques including optical measurement in tensile tests, crack propagation study and an idea of using hydroforming machine as a bending press were presented.

Based on the conclusions of the above-mentioned research, the next part of the work is dealing with mechanical properties of heat affected zone of high strength steels. This paper focuses on strength of the heat affected zone and presents the first part of the conducted research dealing with mechanical properties of the heat affected zone.

Welded joints represent significant parts of some steel structures. Welded connections of common grade steels have been investigated and verified for many years; detailed rules for both welding technology process and structural engineering design therefore are clearly given in design standards [2] and other prescriptions. On the other hand, new or improved techniques of steel processing allow producing structural steel grades with tensile strength exceeding 1300 MPa. However, current European design codes for civil engineering permit usage of steel up to the grade S700 only and for some particular steel types only [3]. The main reason why new high strength steels cannot be used in the engineering praxis is the lack of knowledge about the behaviour of such steels in structures.

The main role of a structural weld is force transmission between two adjacent plates, which means that this connection must show clearly describable mechanical properties, ultimate load capacity and ductility especially. These characteristics are controlled not only by mechanical properties of base material but also considering a technology process and its procedures and quantities as, for instance, heat input, grade, diameter and type of welding consumable used, the welding method, number of passes (single or multilayer welds), preheating level, cooling rate, geometry of the weld and some other.

The welding process always causes changes in adjacent parts of base metal. This affected zone represents the weakest part of the connection in many cases. Therefore, it is necessary to determine the properties not only in the weld material (which in accordance with common rules is sufficiently resistant), but in the heat affected zone as well.

1.2. Influence of thermic conditions
It has been proven by many researchers [4] that resulting mechanical properties of HAZ are influenced especially by thermic conditions during the welding process. They are commonly described by heat input and preheating level, cooling rate and interpass temperature. According to the definition of heat input, a range for cooling rates \( t_{8/5,\text{min}} \) to \( t_{8/5,\text{max}} \) can be calculated. If the minimal preheating temperature and maximal interpass temperature are specified, so-called “working area” for the welding process can be plotted [5,6]. This area determines general requirements for the welding technology settings. The difference in the size of the working area for mild steel S355 and for high strength steel S960QL is displayed in figures 1 and 2. This basic comparison gives clear information about the main difference between welding process for mild and high strength steel: quite strict limitations for HSS make the welding much more difficult and do not allow an in-situ or manual workshop welding in many cases.
2. Experimental program

2.1. Description
Thermomechanically rolled steel S960 MC and directly quenched steel S960 QC were used for determination of the impact of the thermic conditions on mechanical properties of the weld and heat affected zone. Matching and undermatching Stein Megafl flux-cored wires consumables and different heat inputs have been combined within the sample file.

2.2. Test configuration
22 sample plates were welded by combination of three different strength grades of welding consumables and three different heat inputs for the steel S960 MC and 13 sample plates for the steel S960 QC. The welding parameters are shown in table 2.

The sample plates made of the steel S960 MC were welded in the V-shape, the butt weld form and sample plates from the steel S960 QC – in the ½ V-shape. Each welded part of the plate (left and right) was provided by different rolling direction (parallel and perpendicular), see figure 3 and figure 4. Samples for tensile tests were tested without butt weld camber smoothing. Based on that it was possible to forecast that the failure of the tension test would appear in the heat affected zone, which is necessary to determine its mechanical properties.

From every welded sample plate 4-5 tensile samples, 9-10 V-Charpy impact strength and 2-3 samples for hardness measurement were cut by means of a high pressure water jet. Tensile samples and V-Charpy impact test samples from base material for longitudinal as well as for transversal rolling direction were taken as well. The quality of welding was observed using the tests of macrostructure. Due to these tests, it was possible to notice the areas of weld, HAZ and base metal, see figure 5.
Table 1. Chemical composition of base metals.

| Element | S960 MC | S960 QC |
|---------|---------|---------|
| C       | 0.0870  | 0.0950  |
| Si      | 0.2500  | 0.2000  |
| Mn      | 1.8100  | 1.0600  |
| P       | 0.0100  | 0.0090  |
| S       | 0.0010  | 0.0031  |
| N       | 0.0036  | 0.0058  |
| Cr      | 0.0700  | 1.0900  |
| Ni      | 0.2800  | 0.0590  |
| Cu      | 0.0100  | 0.0180  |
| Mo      | 0.4700  | 0.1200  |
| Al      | 0.0400  | 0.0280  |
| Nb      | 0.0030  | 0.0030  |
| V       | 0.0200  | 0.0080  |
| Ti      | 0.1900  | 0.0280  |
| B       | 0.0011  | 0.0018  |

Figure 3. Welded sample plate.  
Figure 4. Scheme of cutting.  
Figure 5. Macrostructure of butt weld.
### Table 2. Welding parameters of samples.

| S960 MC Sample | Electrode | Q [kJ/cm] | S960 QC Sample | Electrode | Q [kJ/cm] |
|----------------|-----------|-----------|----------------|-----------|-----------|
| 1              | MF 742    | 0.9       | 1              | MF 742    | 1.1       |
| 2              | MF 742    | 0.9       | 2              | MF 742    | 1.1       |
| 3              | MF 742    | 0.9       | 3              | MF 742    | 1.1       |
| 4              | MF 742    | 0.9       | 4              | MF 807    | 1.1       |
| 5              | MF 742    | 0.9       | 5              | MF 807    | 1.1       |
| 6              | MF 742    | 0.9       | 6              | MF 807    | 1.1       |
| 7              | MF 742    | 0.9       | 7              | MF 807    | 1.1       |
| 8              | MF 742    | 0.9       | 8              | MF 807    | 1.1       |
| 9              | MF 807    | 0.9       | 9              | MF 1100   | 1.1       |
| 10             | MF 807    | 0.9       | 10             | MF 1100   | 1.1       |
| 11             | MF 807    | 0.8       | 11             | MF 1100   | 1.1       |
| 12             | MF 807    | 0.8       | 12             | MF 1100   | 1.1       |
| 13             | MF 807    | 0.9       | 13             | MF 1100   | 1.1       |
| 14             | MF 807    | 0.9       |                |           |           |
| 15             | MF 807    | 0.8       |                |           |           |
| 16             | MF 807    | 0.8       |                |           |           |
| 17             | MF 1100   | 0.9       |                |           |           |
| 18             | MF 1100   | 1.0       |                |           |           |
| 19             | MF 1100   | 1.0       |                |           |           |
| 20             | MF 1100   | 1.0       |                |           |           |
| 21             | MF 1100   | 0.9       |                |           |           |
| 22             | MF 1100   | 0.9       |                |           |           |

(green – parallel to rolling direction; red – perpendicular to rolling direction).

#### 2.3. Test results

The measured tension strengths of the heat affected zone material are shown in figures 6 - 14.

**Figure 6.** Strength of samples S960 MC.

**Figure 7.** Strength of samples S960 MC.
Figure 8. Strength of samples S960 MC.

Figure 9. Strength of samples S960 MC.

Figure 10. Strength of samples S960 QC.

Figure 11. Strength of samples S960 QC.

Figure 12. Strength of samples S960 QC.

Figure 13. Strength of samples S960 QC.
A mean value of tension strength for all “MC” samples was 1016 MPa, for all “QC” samples – 876 MPa. As it was expected, the principal influence of filler metal grade on tension strength of HAZ was proven. The mean value of tension strength for all samples with MF742 filler metal grade was 804 MPa, MF 807 filler metal grade 840 MPa and MF 1100 filler metal grade 957 MPa.

Different mechanical properties and inclination to material softening of heat affected zone is perceptible for direct quenched steel S960 QC. That phenomenon is caused by lower content of alloy components (as seen in table 1). Mean value of strength for MC with the heat input 0.8 was 1046 MPa, MC with the heat input 0.9 was 996 MPa, MC with the heat input 1.0 was 1029 MPa and QC with the heat input 1.1 was 875 MPa.

No clear correlation between tension strength and the rolling direction has been found. Figure 10 and figure 12 show that in some cases contrary results were obtained – QC steel with MF 807 shows significantly higher strength for “perpendicular” samples but the configuration MC + MF 1100 indicates an opposite trend.

**Figure 14.** Strength of HAZ depending on MF.

**Figure 15.** Ductility of HAZ.

Ductility of all specimen material was very low as it is demonstrated in figure 15. The mean values of ductility for steel S960 MC were 2.75 – 3.25 % and for steel S960 QC 2.5 – 2.75 %.

The V-Charpy tests results are not presented within this paper.

3. Conclusion and future work

All preliminary results, described within this paper, describe the mechanical properties in the HAZ. Both used materials (S960 MC and S960 QC) were welded using three different flux-cored wires and different heat inputs and the principal influence of filler metal grade on tension strength of HAZ was proven. The mean value of tension strength for all “MC” samples was 1016 MPa, for all “QC” samples – 876 MPa. Different mechanical properties and inclination to material softening of heat affected zone is perceptible for direct quenched steel S960 QC (this is caused by lower content of alloy components). However, direct correlation between tension strength and rolling direction was not validated. The follow-up research of our team is aimed at welded connection of I-shape hybrid girders.
4. References
[1] Virdi K and Tenhunen L 2011 Proc. of the METNET Seminar 2011 in Aarhus (HAMK University of Applies Sciences) pp 24–36
[2] EN 1993–1-8: Eurocode 3: Design of Steel Structures – Part 1-8: Design of Joints
[3] EN 1993–1-12: Eurocode 3: Design of Steel Structures – Part 1-12: General – High Strength Steel
[4] IABSE: Use and Applications of High Performance Steels for Steel Structures pp 99–110
[5] Gresnigt A M and Steenhuis C M 1997 High Strength Steels – Construction Research Communications Limited pp 31–41
[6] Davies A C The Science and Practise of Welding, Welding Science and Technology vol. 1

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