WELDED JOINT OF HIGH-STRENGTH STEELS WELDOX 700 AND COMMON GRADE STEEL S 355

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High-strength steels can be effectively utilized for strengthening existing structures or to improve highly stressed elements or structural details fabricated from lower grade steel. When used together with traditional grades of steel, the favourable mechanical properties of high-strength steels open up a wide range of applications in the steel constructions of civil and engineering structures, both in primary structural elements and in individual parts. The paper is concerned with butt and fillet welded joints of components made of high-strength steel with a yield strength of 700MPa and elements made of traditional grade S355 and S235 steel. The technique for welding materials with different strengths and the choice of additive materials for welding are presented in the experimental research.

KEYWORDS

materials technology, steel structures, strength & testing of materials

1 INTRODUCTION

If the yield strength of steel materials exceeds 355MPa, they are usually referred to as high-strength steels. Currently, steels achieve higher and high strength thanks to the manufacturing process. The chemical composition of such materials is the same as that of standard quality steels. During their production, they are subjected to controlled thermomechanical rolling and quenching during rolling with subsequent tempering, which reduces the quantities of alloying substances needed. Accelerated cooling is provided by intensive jets of cold water. It can be said that a portion of the alloying elements is replaced by the intensity of the quenching process. The manufacturing procedure is cost-effective as well as environmentally-friendly. The end product is a fine-grained steel with high yield strength, strength and toughness at low temperatures (down to -60°C). The material has a low carbon equivalent, which has a beneficial effect on its weldability. At present, when designing steel structural elements it is possible to make use of the standard EN 1993-1-1, both for standard quality steel (S235 to S355) and the higher-strength steels S420 and S460. When designing joints and connectors the document EN 1993-1-8 applies, in particular for statically loaded structures made from steel of grade S235 to S460. Standard EN 1993-1-12 supplies additional rules for the option of using steel of strength grades up to S700 in structures. The use of steels with strengths above S700 is not supported in today's standards documents. Welding of the aforementioned steels is defined in EN1011-1 and 2. The rules contained in EN 1993-1-8 apply for the static assessment of the welded joints of elements.

2 FACTORS IN THE DESIGN AND EXECUTION OF WELDED JOINTS

In welding structural elements from high-strength steel, various vital factors have to be taken into consideration. One of the important reasons for the use of modern high-strength steels with yield strengths of 420 to 700MPa is their weldability, as high-strength steels have a lower carbon equivalent value (CEV) than standard quality steels (S235, S355). When it is already necessary to preheat standard quality steel elements because of the thickness of the welded material, high-strength steels of equivalent thickness can still be welded without preheating. This fact can be of high importance if the welding is carried out at a construction site because preheating can be technically demanding. When welding high-strength steels, preference is given to welding without preheating and with limited heat input. If it is necessary to use preheating (for larger connected elements), the selected temperature usually ranges between 100 and 150°C. A high level of strength (i.e. yield strength and ultimate strength) is achieved in high-strength steels via the technique used for their production, i.e. heat treatment. When this heat is applied to the connected elements during welding, it causes further local thermal processing of the material (annealing), which can have a significant impact on its strength at the locations of welded joints. The choice of welding technique and the speed of welding (which is connected with this) have a significant impact on the parameters of welded joints. The speed of welding, together with the intensity of melting, affects the weld as well as its immediate surroundings, i.e. the thermally affected zone. Low speed and intensity can cause a fault of the cold joint type, i.e. the construction elements won´t melt properly at the joint and will fail to connect perfectly. On the other hand, high melting will cause great changes in the mechanical properties of the materials in the HAZ (Fig.1). This factor is particularly important in welded joints where elements fabricated from standard quality steels are combined with those made from high-strength steels, often with different thicknesses. Based on the performed experiments, it can be stated that the critical parts of welded joints, in which steel structural elements made from materials of varying strengths are connected, are the areas of maximum coarsening at the transitions between welded metal and lower-strength steel.

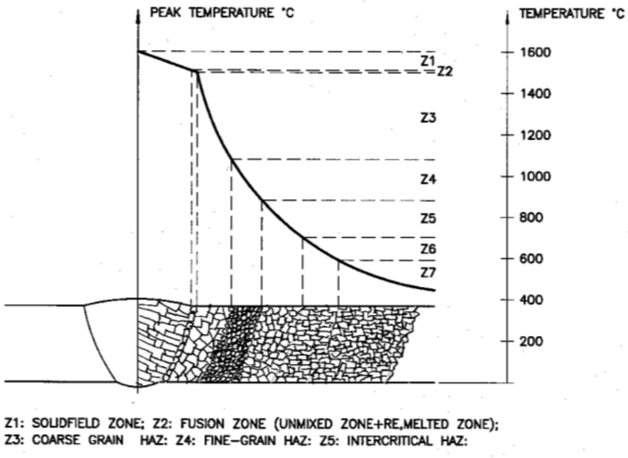

Figure 1. Heat Affected Zone (HAZ)

When materials are divided and welded that is the case for steels of standard strength, since high-strength steels are more sensitive to the intensity of thermal stress. The microstructure of steel in the HAZ changes very significantly according to the effect of heat and simultaneous changes in toughness and hardness.

The most important parameter defining the welding process is the cooling time $t_{8/5}$. The cooling time is the period when materials cool down at the location of a weld from 800 to 500°C. In the case of non-alloyed steels, austenite transforms into disintegration structures, i.e. ferrite, pearlite or martensite. If the weld cools too fast it causes high hardness of the material in the HAZ. The risk of the creation of martensite and the occurrence of cold cracking during weld cooldown is standardly stated to be $t_{8/5} \leq 6$s. Excessively slow cooling, on the other hand, mainly increases the risk of a drop in the strength and toughness of the material in the HAZ below required values. The $t_{8/5}$ values verified in practice range between 6 and 20s depending on the type of material and its thickness. The cooling time $t_{8/5}$ in the HAZ of welded steels can be reliably determined via CCT diagram analysis (anisothermal decomposition of austenite), including the resultant structure of material in the HAZ of steels. Welding parameters can be prescribed according to the required structure of the material in the HAZ (heat input, i.e. mainly the current and speed of welding) so that the required strength and hardness can be achieved after welding. According to the hardness to be achieved, the welding procedure is supplemented via the use of interpass temperature (150 to 225°C) and subsequent heat processing (over 300°C). The maximum acceptable hardness values in the HAZ are defined by the EN ISO 15614-1 standard in the following way: 380HV for steels with an ultimate strength of up to 890MPa, and 450HV for steels with an ultimate strength of over 890MPa. Excessively high hardness in the HAZ can be lowered by subsequent annealing at temperatures of 300 to 440°C with a significantly lower delay for the lowering of residual stress. However, during annealing a drop occurs in the yield strength of material below the values stated in the material sheet. The higher the strength of the material, the more the heat input influences the mechanical characteristics in the area of the welded joint. This factor is particularly significant in the case of manual welding, when the speed of welding is completely dictated by the welder. Generally, if it is possible to implement measures during production (welding) that will eliminate the necessity of annealing to remove tension, it is beneficial to include them in the production process.

3 EXPERIMENTAL RESEARCH

The experimental research described here was conducted at a laboratory at Brno University of Technology, Czech Republic. It focused on issues concerning fillet and butt welds in elements fabricated from high-strength steels as well as welds in combined elements made from standard quality steel and high-strength steels.

Following the completion of high-quality welded joints comprising elements from high-strength steels (or when combining elements from standard quality and high-strength steels) the preheating temperature, interpass temperature and joint cooling time $t_{8/5}$ need to be determined with regard to the required levels of hardness and fracture toughness. An increase in the size of grains in the thermally affected zone of the welded joints can be expected, and thus the lowering of plastic properties in such areas.

3.1 Butt welds on joints of structural members from Weldox 700 and S355

The butt welding of construction elements – metal sheets of the same thickness – was carried out via the MAG – 135 welding method using the Fronius TPS 4000 device and short circuit transfer. Manual welding was performed to simulate the real welding of steel structures in different positions and to minimize heat input in the welded joint when carrying out short arc welding (short circuit transfer). Weld is cut to see various HAZ and five layers (Fig.2).

Table 1. Basic properties of electrodes OK Autrod 12.51

product	R_m [MPa]	$R_{p0,2}$ [MPa]	A_5 [%]	KV (J)/°C	
				-20	-40
OKAutrod 12.51	560	480	26	130	90

Weldingparameters:

Electrode:
OK Autrod 12.51: heat input of welding $Q = 0{,}65\,kJ.mm^{-1}$
WELDOX 700: CET= 0,31%, HD = 5ml/100wm
S355J0: CET = 0,40%
$T_p(S355) = 697 \,.\, CET + 160 \,.\tanh(d/35) + 62 \,.\, HD^{0,35} + (53 \,.\, CET - 32) \,.Q - 328(°C); T_p = 96°C$
$t_{8/5}(2D) = (0{,}043 - 4{,}3 \,.\, 10^{-5} \,.\, T_0) \,.\, Q^2/d^2\,[(1/500 - T_0)^2 - (1/800 - T_0)^2] \,.\, F_2;\ t_{8/5} = 6{,}6s$

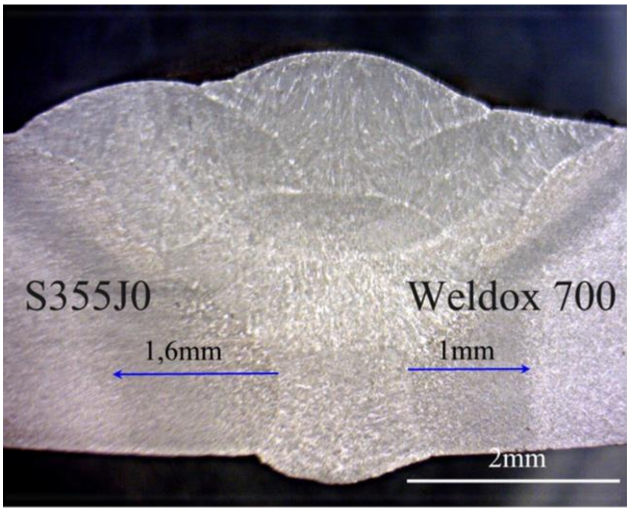

Figure 2. Joint welded using wire electrode OK Autrod 12.51 – five weld beads

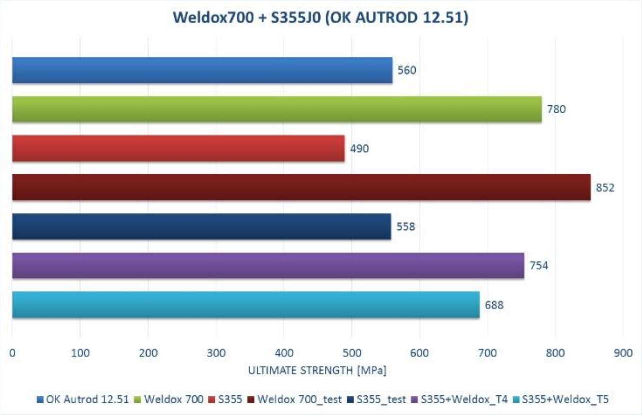

Figure 3. Tensile tests of filling metal, parent metal and welded structural elements from steels Weldox 700 and S355

The tensile testing (Fig.3) of butt welds in adapted samples saw fractures occur at the expected location, i.e. the weakest point of the welded joint. The initiation site for all fractures was the area of maximum grain roughening in the HAZ on the interface between the base material and the weld metal. In all tensile tests performed for joints combining Weldox700 steel with S355 steel, the fracture surface was situated in the steel with lower strength (Fig.4). The resultant strength corresponds to the kinds of steel: In the case of S355 steel, the table value of the ultimate strength is R_m 470 to 630MPa and the test values are 754, 688 and 434MPa. The last test weld had a bubble-shaped flaw in the weld metal; the resultant strength reached was only 434MPa.

Figure 4. Specimen failure – fracture in the HAZ on S355

3.2 Butt welds on joints of structural members from Weldox 700 to Weldox 700

The welding of butt ends of construction elements (metal sheets of identical thickness) fabricated from Weldox700 steel was performed with the alternate use of two kinds of electrode with different mechanical properties, i.e. the OK AUTROD 13.31 wire electrode, and the OK AUTROD 13.29 electrode. The welding was carried out via the MAG mechanized method using the Fronius TPS 4000 device. The burner travelled on an FRC 4 mechanized trolley.

Table 2. Basic mechanical properties of OK Autrod 13.29 and 13.31

product	R_m [MPa]	$R_{p0,2}$ [MPa]	A_5 [%]	KV (J)/°C	
				+20	-20
OK Autrod 13.29	820	750	19	70	50
OK Autrod 13.31	890	850	17	70	60

OK AUTROD 13.31: heatimputofweldingQ = $0,21 kJ.mm^{-1}$
OK AUTROD 13.29: heatimputofweldingQ = $0,35 kJ.mm^{-1}$
WELDOX 700:
CET = 0,31%., HD = 6ml/100wm, thickness =8mm
T_p (W700) = 697 . CET + 160 . tanh(d/35) + 62 . $HD^{0,35}$ + (53 . CET – 32) .Q – 328(°C); T_p = 6,5°C
$t_{8/5}$ (2D) = $(0,043 - 4,3 \,.\, 10^{-5} \,.\, T_0) \,.\, Q^2/d^2\, [(1/500 - T_0)^2 - (1/800 - T_0)^2].F_2$
OK Autrod 13.31: $t_{8/5}$= 2,56s
OK Autrod 13.29: $t_{8/5}$= 8,53s

The welded joint with OK Autrod 13.29 wire reached the ultimate strength R_m= 753MPa, or 719MPa. The weld created with this electrode did not attain the strength values of either the basic or the additional material. The weld fractured in the HAZ. The welding of WELDOX700 material using this electrode can nevertheless be recommended, but the impossibility of achieving the full load-bearing capacity of the joint needs to be considered. The weld with the OK Autrod 13.31 wire reached the ultimate strength R_m = 833MPa, or 808MPa. Both tested samples were torn in the base material and the strength of the given joint exceeded the minimum ultimate strength of the base material guaranteed by the producer. According to the results of the tensile test it can be concluded that a quality weld was created (Fig.5).

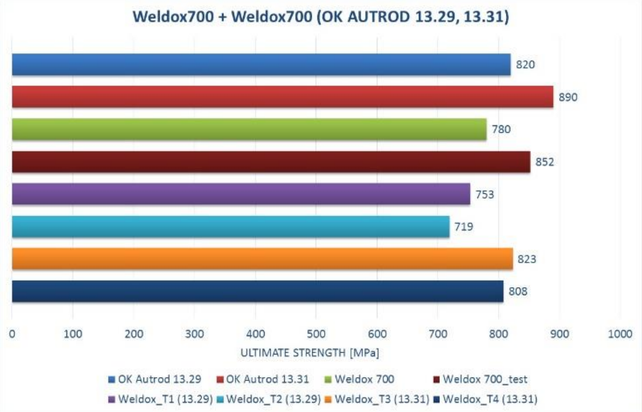

Figure 5. Tensile tests of filling metal, parent metal and welded structural elements from steels Weldox 700and Weldox 700

3.3 Results of hardness tests of butt weld specimens

Hardness HV10 was measured during the metallographic analysis of the welds. The measuring points were arranged from the first base material via the HAZ into the axis of the weld and symmetrically via the HAZ into the second base material.

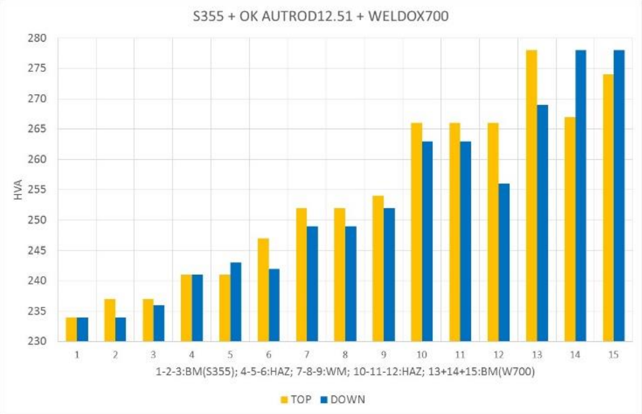

Figure 6. Hardness tests of the Weldox 700 and S355 steels welded joints

The hardness of the weld is one of the important mechanical properties. The hardness measurement result of HV10 demonstrates the different hardness of the base materials. Steel S355 and Weldox700 steel has a hardness (Fig.6) of approximately 272HV in the combination S355-W700. The hardness of the HAZ is slightly lower for W700 then weld metal. The hardness values for the weld metal in the thermally affected area as well as in the basic material in both combinations are surprisingly uniform. The hardness progression of the Weldox700 steel welds corresponds to the higher strength of the OK 13.31 wire electrode and the lower heat input during welding of approx. $0.14 kJ.mm^{-1}$. The hardness 450 HV is on the borderline of the permitted value for high-strength steels according to document ISO 15 614-1.

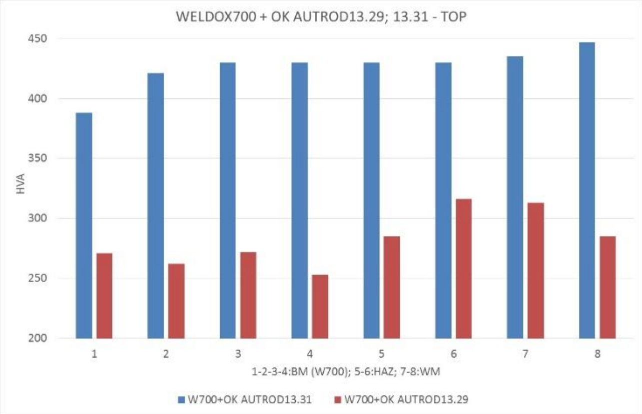

Figure 7. Hardness tests of the Weldox 700 welded joints

4 CONCLUSIONS

Basic advantages of modern high-strength steels include their high level of strength and favourable technological parameters, primarily their very good weldability. These positive properties open up wide possibilities for the use of high-strength steels in the areas of building construction, engineering and for military purposes. Therefore they can be considered building materials with a bright future.

At present, a drawback of high-strength materials in the field of load-bearing building structures, in comparison with the most commonly used steels of standard quality, is mainly the higher (or high) price of the material, the narrow range of products, and also the absence of advanced construction systems which can make full use of the main advantages of the material and eliminate its disadvantages. Also, the lack of experience with the design, realization and operation of load-bearing structures that incorporate elements made from high-strength steels needs to be added to these factors, as well as the absence of (or lack of general access to) knowledge from research into the real behaviour of structures and their parts. One of these areas is the welding of steels of various strengths, which is the subject of the currently described experimental research. Some of the findings obtained in this way are described in greater detail in the previous sections of this article.

The welding of high-strength materials requires a skilled approach to the process itself. The recommended levels of pre-heating need to be respected, particularly in the case of higher strength materials with yield strengths of 900MPa and higher, and with higher material thicknesses. In addition, interpass temperature needs to be monitored: this is 200 - 225°C for S700 steel (up to 300°C according to new recommendations) and 150 - 175°C for steels of higher strengths. The test results confirm high weld strengths when welding Weldox700 steel with high-strength wire electrodes, as well as very good values at the level of the upper strength limit for combinations of standard quality steels S 355 with Weldox700 material. With regard to the very favourable hardness progression in welded joints it can be assumed that the welds also have good toughness. Pre-heating to 80 to 90°C was calculated for the welding of steel S355J0. Preheating to temperatures lower than 100°C is not commonly used, however it is recommended to increase the heat input. Steel Weldox 700 can be welded without preheating. The cooling time $t_{8/5}$ is calculated to be greater than 6s. For welding of elements of Weldox 700 only, a high-speed cooling with cooling time $t_{8/5}$ = 2.6s is calculated. This fact is confirmed by the high level of hardness: 450HV.

The performed experimental measurements – tensile tests of welds and steel hardness tests of in the area of welds - confirmed that desirable properties of welds can be achieved by proper choice of additive materials (electrodes) and welding technology even if the joints are made from materials with very different strengths.

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