27/28th International Conference
ENGINEERING MECHANICS 2022
Milovy, Czech Republic, May 9 –12, 2022
Paper **#97**, pp. 113–116, doi: 10.21495/51-2-113

AN ANALYSIS OF STRENGTHENING MECHANISMS OF TMCP HSLA STEELS

Frátrik M.[*], Mičian M.[**], Winczek J.[***]

Abstract: *The article deals with an analysis of individual strengthening mechanisms used on microalloyed high-strength steel S960MC. The analysis was performed on the basis of theoretical knowledge, measured physical-metallurgical properties, microstructure, and chemical composition. Some of the used material constants were obtained by our own physical simulations on the base material in order to achieve the most accurate results. This knowledge will help explain the soft zone formation that is formed when welding some types of thermo-mechanically controlled processed and quenched steels. Based on these findings, it will be possible to adapt the welding process in order to minimize the degradation of base material in the heat-affected zone and thus reduce the decrease in mechanical properties of welded joints.*

Keywords: S960MC, Strengthening mechanisms, Softening effect.

1. Introduction

Welding of higher grades of thermo-mechanically processed (TMCP) and quenched steels are accompanied by the soft zone phenomenon. This decrease in hardness in the heat-affected zone (HAZ) is caused by metallurgical changes in the microstructure of base material (BM), which is mainly formed by unstable phases of martensite, bainite, tempered martensite or tempered bainite. The creation of the soft zone during welding of mentioned steel types is mainly influenced by applied strengthening mechanisms. One of the main advantages of high-strength low-alloy (HSLA) steels is the resistance to the formation of cold cracking at higher thicknesses and strength ranges. This resistance results from the application of several strengthening mechanisms, which are not based on an increase of perlite in a steel. Characteristic strengthening mechanisms for HSLA steels are grain boundary strengthening (grain refinement), solid solution strengthening (substitution, interstitial), precipitation and dislocation strengthening. The application of several strengthening mechanisms is also reflected in the weldability of HSLA steels. This is generally considered to be good, but is influenced by many factors based on chemical composition, microstructure and mentioned strengthening mechanisms. An example is the formation of the soft zone in the HAZ of TMCP and quenched steels.

Based on the knowledge from the field of metallurgy of construction materials, it can be simply argued that the yield strength of steels is derived from the interaction of several structural factors to the dislocation motion. Mathematically, this interaction can be expressed by the linear equation based on the theory of polycrystalline strengthening, which is expressed as an equation (1) (Ren, 2019):

$$\sigma = \sigma_0 + \sigma_s + \sigma_p + \sigma_d + \sigma_g \tag{1}$$

where σ_0 is the internal lattice stress; σ_s is the solid solution solidification due to substitution and interstitial elements; σ_p includes precipitation hardening; σ_d is the strengthening that occurs when the dislocation motion is slowed down due to the increased dislocation density; σ_g is the strength increase due to reduction in grain size.

[*] Ing. Martin Frátrik: University of Žilina, Faculty of Mechanical Engineering, Univerzitná 1, 010 26 Žilina, SK, martin.fratrik@fstroj.uniza.sk

[**] doc. Ing. Miloš Mičian, PhD.: University of Žilina, Faculty of Mechanical Engineering, Univerzitná 1, 010 26 Žilina, SK, milos.mician@fstroj.uniza.sk

[***] dr hab. inż. Jerzy Winczek, prof. PCz.: Faculty of Mechanical Engineering and Computer Science, Czestochowa University of Technology, Dabrowskiego 69, 42-201 Czestochowa, Poland; winczek@imipkm.pcz.czest.pl

The increase in the strength caused by the solid solution σ_s determines the strengthening due to the presence of alloy elements that are substituted or interstitially dissolved in the matrix. The influence of the chemical composition on the total increase of the yield strength can be expressed by the formula (2):

$$\sigma_s = 37[Mn]+83[Si]+59[Al]+38[Cu]+11[Mo]+33[Ni]-30[Cr]+680[P]+2918[N]+4570[C] \quad (2)$$

where [X] represents the weight fraction of element X in the ferrite (Zhang et al., 2015).

The dislocation strengthening σ_d can be expressed as (Taylor, 1934, Zhang et al., 2015):

$$\sigma_d = 2 \cdot \alpha \cdot G \cdot b \cdot \rho_d^{1/2} \quad (3)$$

where α is a constant depending on the crystal structure (0.5 for the ferritic lattice); G is the shear modulus (8×10^4 MPa for Fe); b is the Burgers vector (0.25 nm) and ρ_d is the dislocation density (m^{-2}). (Ren, 2019, Charleux et al., 2001). The increase in strength due to grain refinement σ_g is described by the Hall-Petch equation (4), which describes the linear relationship between the average size of the ferritic grain and the increase in strength (Charleux et al., 2001):

$$\sigma_g = k_y \cdot d_\alpha^{-1/2} \quad (4)$$

where k_y (MPa · $mm^{1/2}$) is a coefficient expressing the effect of grain size on the increase in yield strength; d_α (mm) is the average ferritic grain size. The coefficient k_y has a different value for each material, which can differ significantly and is therefore determined experimentally for each material. In the case of high-strength steels, the value of k_y is at the level of 21 – 23,5 MPa · $mm^{1/2}$ (Kostryzhev et al., 2014). Precipitation strengthening σ_p is increasing the yield strength by the suppression of dislocation motion by incoherent and non-deformable precipitates (Orowan bypassing). Mathematically, this relationship is expressed by the Ashby-Orowan model (Zhang, 2015), Eq. (5):

$$\sigma_p = 9{,}995 \cdot 10^3 \cdot \frac{f^{1/2}}{d} \cdot \ln(2{,}417d) \quad (5)$$

where *f* is the volume fraction of precipitates in the matrix (%), *d* is the average size of the precipitates (nm).

2. Analysis of strengthening mechanisms of S960MC steel

High-strength structural steel S960MC is produced by a thermo-mechanical controlled process. For S960MC steel, the increased strength is achieved mainly on the basis of grain refinement (σ_g), precipitation strengthening (σ_p) by precipitates of type (Ti, Nb) (C, N) and dislocation strengthening (σ_d) based on multiple deformation in the rolling process. The microstructure of steel, which consists of fine-grained tempered martensite and bainite, is shown in Fig.1.

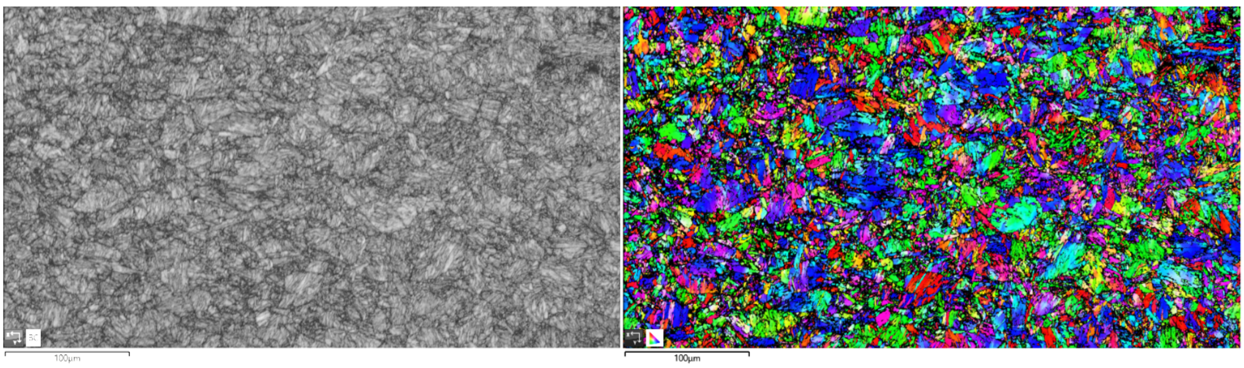

Fig. 1: Microstructure of S960MC steel (EBSD)

Chemical composition according to the inspection certificate is given in Tab.1 and mechanical properties according to experimental measurements are given in Tab.2.

Tab. 1: Chemical composition of Strenx 960MC according to the inspection certificate (wt.%).

C	Si	Mn	P	S	Al	Nb	V	Ti	Cu	Cr	Ni	Mo	N	B
0,085	0,18	1,06	0,01	0,003	0,036	0,002	0,007	0,026	0,01	1,08	0,07	0,109	0,005	0,0015

Tab. 2: Mechanical properties of Strenx 960MC

$R_{p0,2}$ [MPa]	R_m [MPa]	A_{min} [%]	CET/CEV [-]	KV -20°C [J]
1007	1092	8	0,26/0,50	32

*CET/CEV – carbon equivalent

The stress increment due to the lattice friction σ_0 has a value of 53 MPa for the S960MC steel (σ_0 value of the ferritic lattice) (Ren, 2019). Equation (2) is used to calculate the stress increase due to the solid solution σ_s, into which the data on the chemical composition from Tab.1 are inserted. The calculation is based on the content of elements in the solid solution, taking into account only elements (or their share) involved in the solid solution strengthening. In the case of S960MC steel, which is precipitation-strengthened by precipitates of type Nb, V (C, N) and Ti (C, N), it can be assumed that part N and C is bound in the form of precipitates and therefore this fact must be taken into account. Therefore, a value of 0,01% is considered in the calculation for C and N (Ren, 2019) and thus the value of the σ_s for S960MC is 109 MPa. To compute the stress increase by the grain refinement σ_g is necessary to determine the value of coefficient k_y. The k_y was determined on the basis of physical simulations performed on a Gleeble 3500 device. Samples of S960MC steel were heated to 1000, 1200 and 1350 °C. After microstructural analysis of samples a mean grain size of 6,2 µm, 14 µm and 33 µm was determined. The samples were also subjected to a tensile test. After comparing the relationship between grain size and yield strength, the value of $k_y = 21{,}94$ MPa· $mm^{1/2}$ was determined. The average ferritic grain size of BM was determined to be 5,2 µm based on the EBSD analysis. Based on equation (4), the value of σ_g for S960MC is 304 MPa. Dislocation strengthening also plays an important role in thermo-mechanically processed S960MC steel. The increase in yield strength consists in increasing the dislocation density by multiple plastic deformation in a rolling process (Ren, 2019). For the S960MC steel, the value of the dislocation density ρ_d was estimated at the level 1×10^{14}. This value was set according to comparable steel types with S960MC steel (Rešković, 2020, Charleux et al., 2001). After substituting into equation (3), it is possible to determine the approximate stress increment due to the dislocation strengthening σ_d at the level of 200 MPa.

To estimate the increase in stress due to the precipitation strengthening it is necessary to analyze the size and volume fraction of all types of precipitates in steel. Due to the complexity of the analysis, the increase in strength σ_p for S960MC steel was calculated on the basis of the known yield strength by the relation (6):

$$\sigma_p = \sigma - (\sigma_0 + \sigma_s + \sigma_d + \sigma_g) \tag{6}$$

The estimated increase due to precipitation hardening for S960MC steel is thus 342 MPa.

Similar approach to the analysis of strengthening mechanisms was applied to the individual subzones of the HAZ, whose mechanical properties were determined based on the physical simulations on a Gleeble 3500 device (Mičian, 2021a, Moravec, 2013, Hadzima, 2019). The samples were exposed to temperatures of 650, 800, 1000 and 1200 °C, which are values comparable with each subzone. All samples were subjected to tensile test and hardness test. The results of these tests are given in Tab.3

Tab. 3: Mechanical properties of experimental samples

S960MC	20°C BM	650°C SCHAZ	800°C ICHAZ	1000°C FGHAZ	1200°C CGHAZ
Rp0,2 [MPa]	1007	823	643	804	690
Rm [MPa]	1092	840	830	920	809
HV10	361	287	251	282	260

The influence of the individual strengthening mechanisms for each subzone was calculated on the basis of variables such as grain size and dislocation density. Different grain sizes were taken into account for CGHAZ and FGHAZ. The dislocation density was determined for each subzone based on the hardness values (Graça et al., 2008). The value of precipitation strengthening was also determined on the basis of equation (6). The given values approximately correspond to the hardness values measured on real welded joints, which are published by Mičian (2021b).

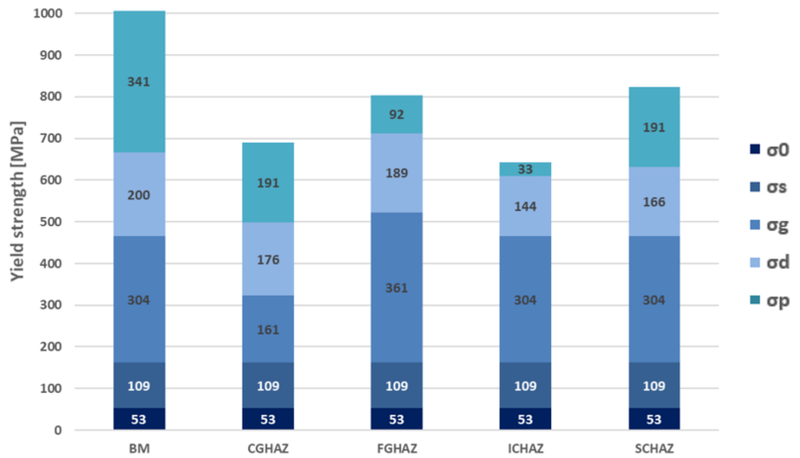

Fig. 2: Analysis of the strengthening mechanisms for individual subzones of the HAZ of S960MC welded joints

3. Conclusions

The influence of the individual strengthening mechanisms on the properties of the HAZ of welded joints was analyzed. It has been shown that the decrease in hardness in the HAZ of TMCP steels is mainly caused by an increase in austenitic grain size, a decrease in dislocation density and coarsening of precipitates. It is important to note that the values of dislocation density and precipitation strengthening were determined only by estimation and more thorough experiments are needed to determine them more accurately. The given knowledge can be useful for setting up the welding process of steels susceptible to the soft zone formation, such as TMCP or quenched steels.

Acknowledgement

This research was funded by APVV and VEGA, grant number APVV-16-0276, grant number APVV-20-0427, grant number VEGA 1/0741/21

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