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ANALYSING THE HAZ SOFTENING OF S960M BY PHYSICAL SIMULATION

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INTRODUCTION

The application of the modern high strength steels obtains an important role in automotive industry. In such cases, the thickness of the structural elements can be decreased together with the mass of the structure and the welded joints. In general, we can state that the increasing of the yield strength, the applied thickness decreases, so the amount of the filler material and the time of the welding decrease, as well. On the other hand, it is important to note, that the costs of these steels are two or three times higher than the average steels, furthermore the price of filler materials are even higher, and the weldability of these materials are more complex. At the same time, the typical manufacturing technology is the welding, which – because of the heat input – modifies the original microstructure of the base material. Therefore, different mechanical characteristics (e.g. strength, toughness, hardness distribution) can be achieved, which is not acceptable in many cases in terms of the construction. Consequently, there is great significance of testing the welded joints of these steels, and the development of the suitable manufacturing technology. Accordingly, the properties and the weldability of VOESTALPINE ALFORM 960M (S960M, no standard mark available yet) thermomechanically rolled high strength steel were investigated.

In many cases it is impossible to investigate certain heat affected zones of a real welded joint, because during the real process the thermal gradient is so high in the material, that strong inhomogeneous microstructure occur, which is changing in 0.1 mm-s. Applying physical simulation homogeneous samples in high amount can be prepared, aimed to following mechanical tests, like impact, fracture toughness and microstructural analyses.

The paper aims to conduct a series of experiments and behaviours which make it possible to measure the objective data on the basis of the obtained image of the steel strips tested with heat-affected zone tests in a physical simulator. Generally the difficulties encountered are: cold cracking, HAZ softening and the toughness and/or strength reduction in HAZ. Therefore all the experiments carried out on the weldability of S960M high strength steel will be highlighted below and discussed with more details.

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THE INVESTIGATED THERMOMECHANICALLY ROLLED MATERIAL

In the ’70 years a new process, called thermomechanical rolling was developed to achieve outstanding strength and advanced weldability properties.

The most effective method of increasing the yield-strength, so the production of high-strength steels is the decreasing of grain size. In this case the yield strength can be increased without changes in chemical composition. The fine grained microstructure, the decrease of the grain size can be achieved by different methods [1] (N = normalised, TM = thermomechanically rolled, Q = quenched, DQ = direct quenched), illustrated on Fig. 1.

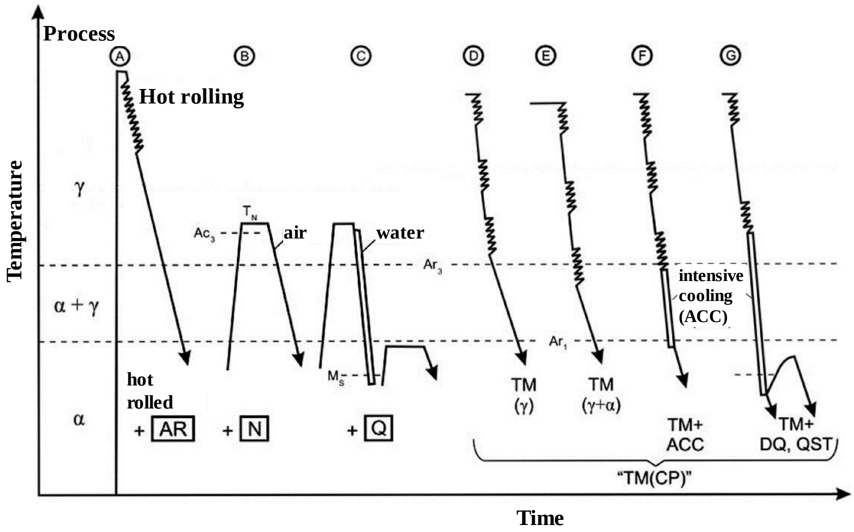

Fig. 1
Different production methods of high strength steels [2]

When TMCP is chosen as the process route, the rough steel section (i.e. the slab) is heated to a temperature regularly used for hot working operations (about 1200 °C). The initial hot working ('roughing') is carried out in a normal way, but the final hot work reduction or 'finishing pass' is carried out at a lower temperature than would be used for older processes. Plastic deformation at this lower temperature promotes fine grain sizes and retards precipitation. The final hot working may continue down to temperatures below the Ar_3 critical temperature (transformation from austenite to ferrite). This requires heavy rolling equipment capable of deforming the steel at low hot working temperatures. The optimum precipitate size and dispersion is obtained when the finish rolling temperature is around 775 °C.

The cooling which follows brings the steel to the transformation temperature range, and the austenite to ferrite transformation results in fine ferrite grains and fine dispersed precipitates. For some TMCP steels, this last stage of cooling, when the transformation is completed, is accelerated by water cooling, to give a finer grain size. Accelerated cooling can sometimes result in bainite formation as well as, or instead of, ferrite formation. This production process (TMCP) can be seen in Figure 2.

As the experimental work is carried out on the thermomechanically rolled high strength steel, S960M, (Alform960M) designed and certified by Voestalpine. The further discussion will focus on this steel grade. In Table 1 the chemical composition of this is given [1].

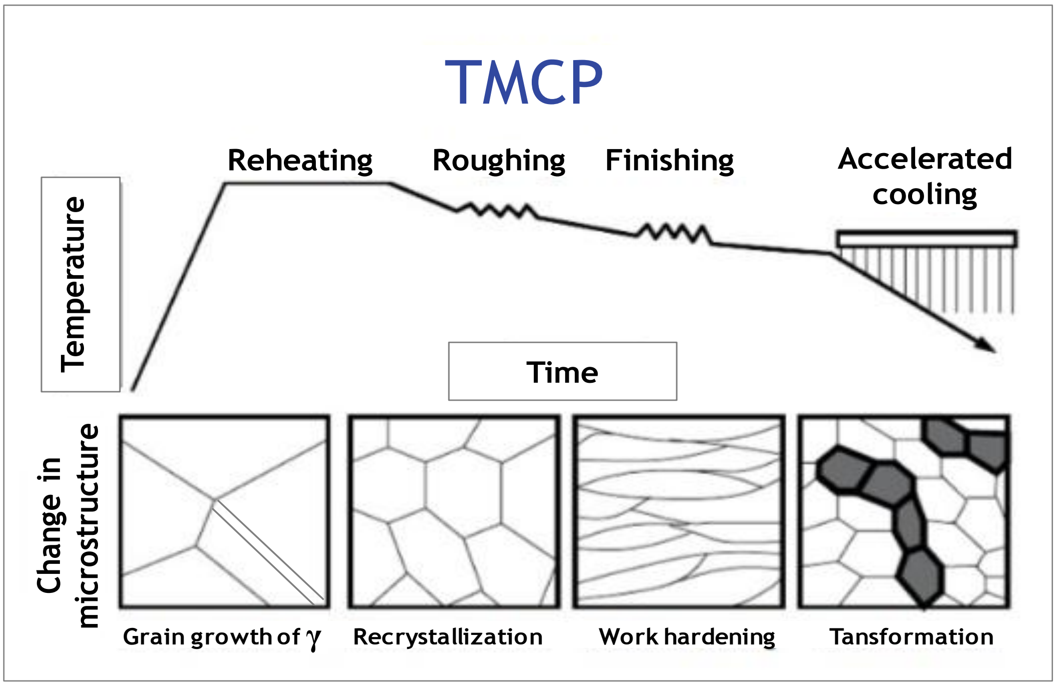

Fig.2

Schematic illustration of the thermal cycle and change in microstructure [3]

As we can see, the carbon content of this steel is lower than the general structural steels. On the other hand, the amount of the other elements is not so different compared to the normalized structural steels. The carbon equivalents of these steels are relatively low.

Table 1

The chemical composition of Alform S960M in mass percent [4]

Alform 960M	**C**	**Si**	**Mn**	**P**	**S**	**Al**	**Cr**
	0.084	0.329	1.650	0.011	0.0005	0.038	0.61
Mo	**Ni**	**V**	**Nb**	**Ti**	**Cu**	**N**	**B**
0.29	0.026	0.078	0.035	0.014	0.016	0.006	0.0015

In case of the weldability this is considerable an advantage, but on the other hand, the complex microstructure made more difficult to weld these steels. With the higher toughness and the advantageous chemical composition the resistance against the cold cracking is also higher in these steels.

Due to the very low carbon level and the absence of elements used to increase the hardenability such as chromium and molybdenum S960M steels have relatively low welding carbon equivalents. The Figure 3 shows the Graville diagram predicting weldability. Here the carbon concentration is plotted versus a special carbon equivalent (extended with the Si content) calculated as

$$CE=C+(Mn+Si)/6+(Cr+Mo+V)/5+(Cu + Ni)/15, \% \quad (1)$$

The Graville diagram is divided into three zones. In Zone I welds produced under most welding conditions are not susceptible to cracking, in Zone II welding requires controlled heat input and in Zone III the heat-affected-zone (HAZ) is extremely susceptible to cracking, therefore preheating and controlled heat input are needed at the same time [3].

As evident from the Figure 3 below it can be clearly seen, that the examined base material are in the simplest weldable category (I.), while the other, alternative high strength steels (e.g. quenched and tempered category) are located in the hardly weldable category (III.)

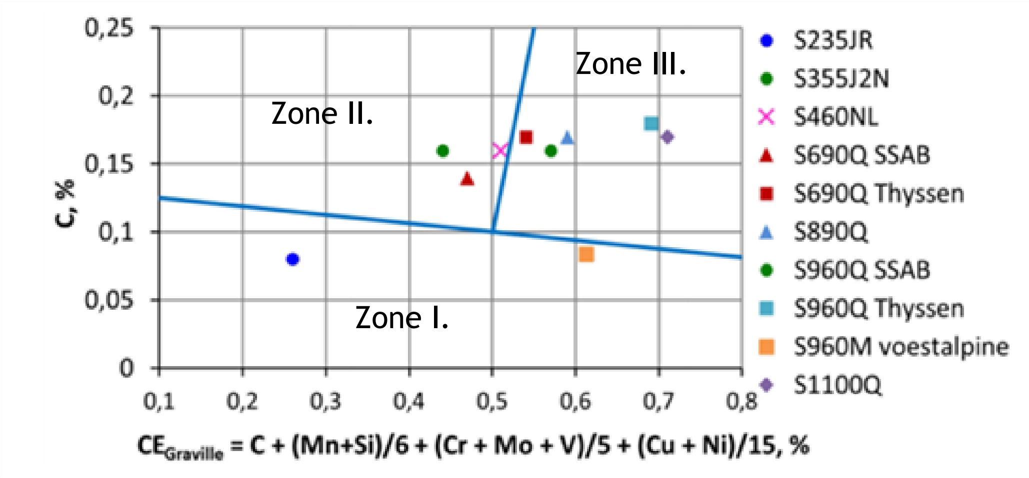

Fig. 3
Graville diagram [3]

Further problems can be, that the heat-affected zone (HAZ) can be easily hardened, furthermore, in case of too large heat input the heat affected zone can be softened comparing to the base material, which can cause strength and hardness decreasing [5]. Of course, both cases are intolerable. According to the material certificate from the company VOESTALPINE the mechanical properties of the investigated material are as follow: $R_{p0.2}$= 1051 MPa, R_m=1058 MPa, A_5=16.9% [4].

A 15 mm plate thickness was selected as base material for the physical simulation experiments. A precise preparation of HAZ specimen is needed with required geometrical shape (10 × 10 × 70 mm) and good surface quality. The experimental work was carried out on 12 samples.

EXPERIMENTAL PROCEDURE

On the presented thermomechanically rolled high strength steel HAZ tests were performed in a new generation of thermomechanical simulators, called Gleeble 3500, installed in the Institute of Materials Science and Technology of the University of Miskolc [6], [7], which is capable for the reproduction of real material processing (e. g. welding, heat treating and metal forming) in laboratory circumstances.

On the Fig 4 one of the investigated samples can be seen with a type K (NiCr-Ni) thermocouple, which was welded onto the middle of sample for temperature record and control by means of the induction heating.

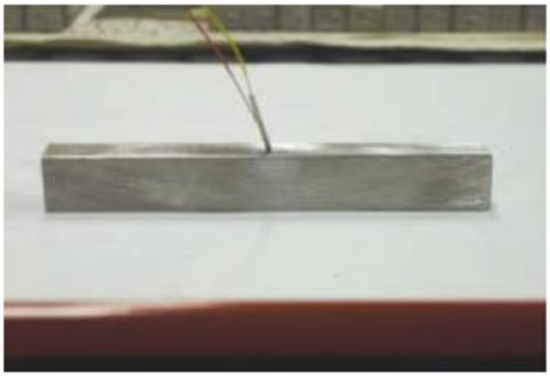

Fig. 4
Thermocouple welded on specimen

The maximum temperature, holding time, cooling rate of the thermal cycle parameters were selected according to the possible procedures during the gas metal arc welding. Heat cycles were determined according to the Rykalin 3D model, where the whole heat cycle, including heated part as well, was described by time-temperature points instead of automatic software settings. Although more welding heat cycle models (Hannerz, Rosenthal, Rykalin) are available in QuickSim software developed for the simulator, the GSL programs were manually written, using the time and temperature points determined by Rykalin-3D model. In order to simulate the different HAZ areas, samples were heated to different peak temperatures in the range of 450 ºC – 950 ºC and a fast ($t_{8.5/5}$ time around 5 s) and a slow cooling rate ($t_{8.5/5}$ time around 30 s) were used.

The time and temperature points of the desired HAZ heat cycle was calculated by EXCEL using the original Rykalin-3D model [8]:

$$T(R,x) = \frac{E_v}{2\pi\lambda R} e^{-\frac{v}{2a}(x+R)} \quad (2)$$

$$R = \sqrt{x^2 + y^2 + z^2} \quad (3)$$

$$a = \frac{\lambda}{c_p \rho} \quad (4)$$

Where: E_v: linear energy (heat input per unit length of weld)
λ: thermal conductivity ρ: density
v: speed of heat source c_p: specific cheat at constant pressure.

The aim of the experiment is to detect the softening/hardening in several zones in the HAZ, like SCHAZ, the sub-critical zone, ICHAZ, the intercritical zone, FGHAZ, the fined grain zone, CGHAZ, coarsened grain zone. Gaining to comprehensive analysis of the whole HAZ, results for 775 and 1350 °C are involved from the literature [9]. The realized HAZ cycles for the two technological variants $t_{8.5/5}$ = 5 s and $t_{8.5/5}$ = 30 s are illustrated in next figures.

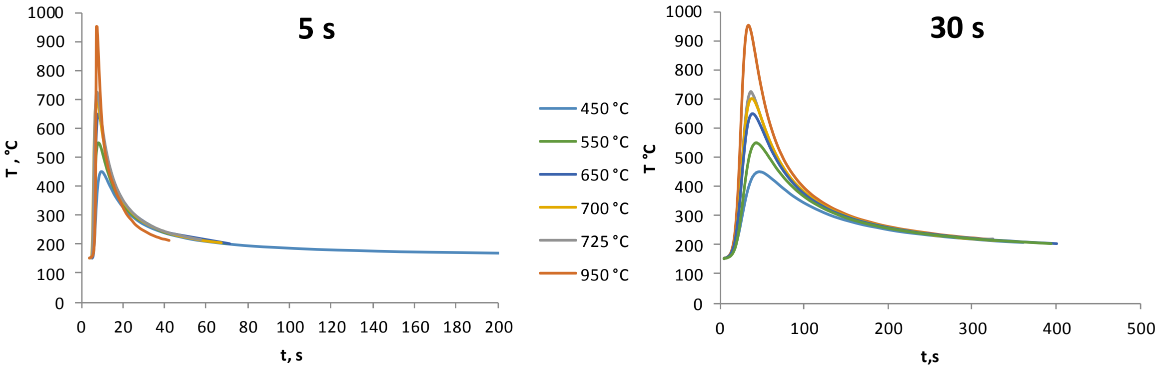

Fig. 5
Time-temperature curves used in the Gleeble simulations with $t_{8.5/5}$=5 s and 30 s

After the thermal process, the simulated specimens were perpendicularly cut their longitudinal size at the thermocouples and a Reicherter UH 250 Universal Hardness Tester, was used for the hardness examination, F=100 N, t=10 s. The hardness measurement was carried out on five points on the surface of the cross section. Four points for each corner of the surface and one point in the middle of cross section, precisely beside the mark of the thermocouple. The HV hardness test results are presented for the two different applied cooling times on Figure 6. and 7.

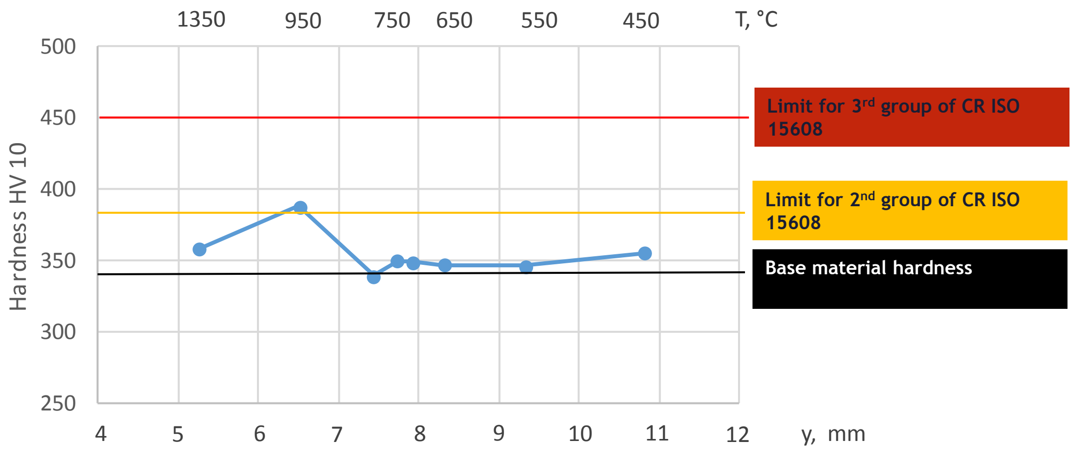

Fig. 6
HV10 test results for 5 s cooling time

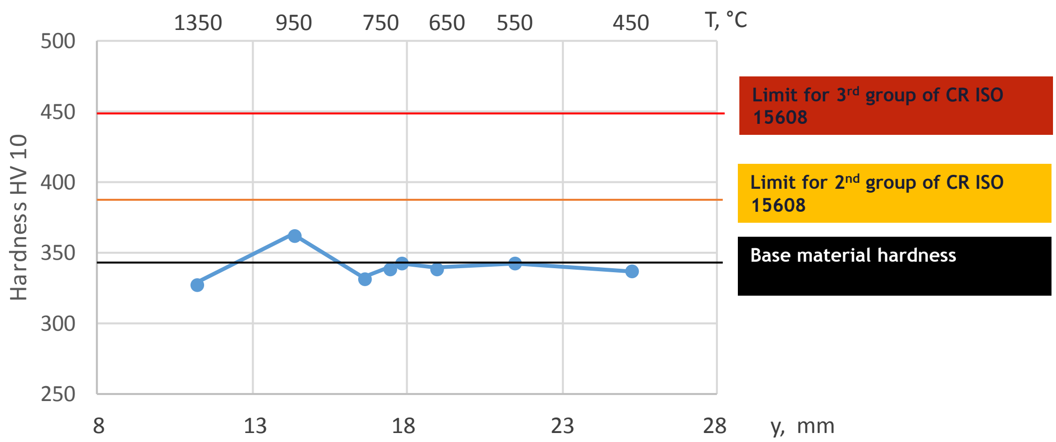

Fig. 7
HV10 test results for 30 s cooling time

All heat affected zones fulfilled the requirement of the governing standard according to the third group of steels. However the standards of the second group of steels was not fulfilled. The hardness of the base material approximately 340 HV. According to the hardness tests we can conclude that the S960M steel respected the safety value required by the standards [10], [11].

Indeed the results values did not exceed the maximal hardness value 450 HV10 as shown in the diagrams on the Figures 6 and 7. However an important notification could be detected which has occurred during the short cooling time. In fact it could be observed that the hardness limit from the former conventional standards of TM steels with the maximal value 380 for the 2^{nd} group of EN ISO 15614-1 for the lower yield strength steel > 500 MPa was exceeded by the ALFORM S960M with the much higher yield strength (960 MPa) than the conventional TM steels.

A small hardening was noticed in the SCHAZ zone of the TM S960M at the shorter cooling time which is not significant. In contrary to the shorter cooling time at the SCHAZ in the longer cooling time we could notice a slight softening which nevertheless still smaller than the softening of the quenched and tempered steel S960Q with the same yield strength. A small softening was noticed also in the ICHAZ of the TM S960M steel area with the longer cooling time.

In the FGHAZ zone of our steel we could remark a big hardening at the short cooling time which is decreasing in the shorter cooling time, however this result is not alarming because of the microstructure of the fined grain in heat affected zone. In fact the grain size is small and the microstructure can pretend to a good toughness.

And finally in the CGHAZ we can observed a slight hardening at the shorter cooling time, which was much lower than in the quenched and tempered steel [5].

CONCLUSION

The present paper represents results of physical simulation experiments on the HAZ of S960M advanced high strength structural steel. The Rykalin 3D model was suitable related to the thickness 15 mm and was programmed with Quicksim software of Gleeble 3500 physical simulator available in the laboratory of the Institute of Materials Science and Technology. The applied $t_{8.5/5}$ cooling times were between 5 and 30 s, appropriate to GMAW parameters, while six peak temperatures 450 ºC, 550 ºC, 650 ºC, 700 ºC, 725 ºC (SCHAZ) and 950 ºC (FGHAZ) were investigated during the experimental work.

According to the hardness tests all of the performed HAZ areas fulfilled the maximum allowed 450 HV10 hardness, permitted by the governing EN ISO 15614-1standard for the 3^{rd} steel group in CR ISO 15608 standard. However we could notice that the maximal value for the conventional TM steels for the 2^{nd} group with lower yield strength was exceeded. In our opinion the conventional standards should be revised and upgraded for this new thermomechanical steels since the slight hardening in the FGHAZ is not relevant in terms of the cold cracking.

We also recognised, that the hardness reached much lower average values by different cooling times compared to the quenched and tempered high strength steel (S960QL) in the same strength category.

There was no significant softening noticed in SCHAZ. A little softening was noticed at the longer cooling times, but it was not remarkable at the higher temperatures. The ICHAZ (775 ºC) tends to soften rather than the investigated SCHAZ areas.

On the basis of hardness test results these steel has lower tendency for cold cracking. As it was expected, even hardening of the coarse-grained HAZ zone was not significant and with the increase of cooling time the hardness was decreasing. There was not a significant hardening of the inter-critical HAZ and sub-critical HAZ areas in the investigated $t_{8.5/5}$ cooling time range.

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