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Simulation of Thermal Cycles at Welding of the Heat Resistant Steel X20CrMoV12.1, Structural and Mechanical Rehabilitated by Specific Heat Treatments

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Abstract

The heat resistant steel X20CrMoV12.1 worked on a thermal circuit at high pressure and temperature (560 °C, 140 MPa), for long time (98,000 hours). During this period, owing to the structural transformations, the mechanical characteristics of the weld and the base metal, as tensile strength and toughness, were been decreased.

Structural and mechanical rehabilitation of this steel was been performed, by applying the specific heat treatments (primary and secondary), in order to obtain the mechanical and structural characteristics, close to the values of delivery state.

The evaluation of metallurgical behaviour to welding of this steel is based on the thermal cycles simulation, followed by specific heat treatments, using prismatic samples type REZ (11x11x55mm) and TRAC samples (Ø 5.5x60mm).

The main structural and mechanical characteristics in the affected zones by welding thermal cycle, were been determined by macro and microscopic analysis and short-term mechanical tests (tensile test, bending impact tests, hardness test). These tests are made on the simulated and reheated samples in two variants (S + R1, S + R2).

Finally, it is shown the possibility to weld this steel, in the industrial practice, after the structural and mechanical rehabilitation.

Key words: *heat resistant steel, thermal cycle, simulation, reheating, REZ samples, TRAC samples*

Introduction

Owing to the high heating rate during the welding and high thermal conductivity of the base metal (BM), the heat-affected zone (HAZ) is subjected to the high cooling rates. In these zones, some phases and hard constituents with low ductility can appear. These zones have, in the most cases, hardened locations, which are approximately in the same place with the maximum residual stresses. Sometimes, these zones can have the additional internal tensions, resulted from the volume increasing owing to the structural transformation. Depending on their level and the correlation with other brittleness factors, the welded joints can have cracks.

The decreasing of the residual stresses can be achieved by applying the specific post-welding heat treatments. In practice, it is made a reheating of the heat-affected zones, which has many metallurgical implications, having a favourable or unfavourable influence on some structural and mechanical characteristics influencing the behaviour of welded joints, in service [1].

The simulation of the welding cycles is a method to research the welding behaviour of the steels. So, the thermal cycles applied to the alloyed steel lead to the specific zones appearance (HAZ simulated). In these zones, there are developed some structural transformations, similar to those of the heat-affected zones of the welded joints (HAZ). Extending these transformations allows the researching of the brittle phenomena by simulation, and observing the structural transformation due to the application of specific post-simulation heat treatments [2].

Taking into consideration that, some weldable stainless steels are susceptible to cracking by reheating, the presence of Cr, Mo, W carbides in the base matrix or at the grain boundaries can have a negative influence. In this paper, there are presented the results of the thermal cycles at welding of the heat resistant steel, X20CrMoV12.1, structural rehabilitated by specific heat treatments. The aim of the paper is to evaluate the susceptibility to brittleness and the cracking phenomena, and to testify the possibility of welding in the industrial practice of this alloyed steel [3].

Characterization of the Heat Resistant Steel X20CrMoV12.1, Structural and Mechanical Rehabilitated

Weldable steel X20CrMoV12.1 is used in the fabrication of some elements and parts for pipes, boilers and power plants, working for long time to high pressures (over 15 MPa) and temperatures between 540 and 600 °C. Also, this steel is used to make the pipes, manifolds for superheated steam, heat exchangers, etc.

1. Chemical composition of X20CrMoV12.1 steel for the live steam pipe, Ø 273 x 28 mm, structural and mechanical rehabilitated after 98,000 hours working in CET Halânga, is presented in the table 1. Also in this table, there are introduced the values of the chemical composition of X20CrMoV12.1 steel according to DIN 17175.

Table 1. Chemical composition of X20CrMoV12.1 steel

Steel	**Chemical composition, %**							
	C	**Mn**	**Si**	**Cr**	**Mo**	**P**	**S**	**Other elements**
0	1	2	3	4	5	6	7	8
Pipe Ø 273x28 mm X20CrMoV12.1 rehabilitated	0.20	0.54	0.23	11.58	1.15	0.030	0.030	V=0.26 Ni=0.56
X20CrMoV12.1 DIN 17175	0.17-0.22	0.30-0.80	0.10-0.50	10-12	0.8-1.20	Max 0.030	Max 0.030	V=0.25…0.31 Ni=0.30…0.80

It can be observed that, the chemical composition of the steel X20CrMoV12.1 in rehabilitated state is according with the composition specified in DIN 17175.

2. The mechanical characteristics of resistance, deformability and toughness of the X20CrMoV12.1 steel in structural rehabilitation state are within the required values for this steel to DIN 17175 (Table 2).

3. The structure of X20CrMoV12.1 steel, in delivery state according to STAS 3478 - 86 is ferritic with martensitic zones and fine carbides of Cr, Mo, V, placed inter-intragranular (Figure 1).

Table 2. Mechanical characteristics of X20CrMoV12.1 steel

Steel	**Yield point $Rp_{0,2}$ [N/mm^2]**	**Tensile strength, Rm [N/mm^2]**	**Elongation, A_5 [%]**	**Reduction of area, Z [%]**	**Fracture energy, KU at +20°C [J]**
0	1	2	3	4	5
X20CrMoV12.1 rehabilitated	725	570	20	54	63
X20CrMoV12.1 DIN 17175	690-840	Min. 490	Min. 17	Min. 40	Min. 34

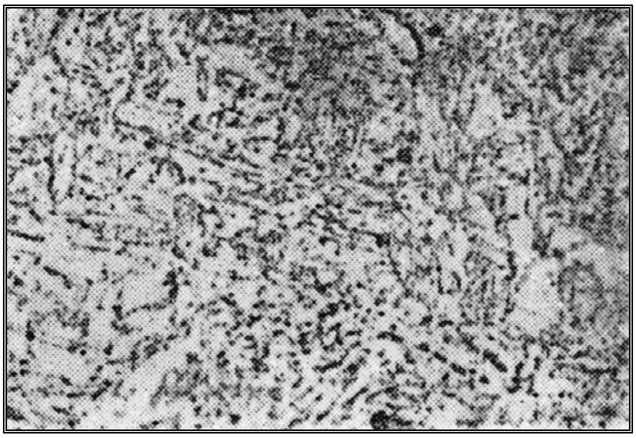

Fig. 1. X20CrMoV12.1 steel, initial state
[Etched HCl, 500x]

In the structural rehabilitated state, X20CrMoV12.1 steel has a complex ferritic-martensitic structure with Cr, Mo, V carbides, placed in the base matrix (Figure 2).

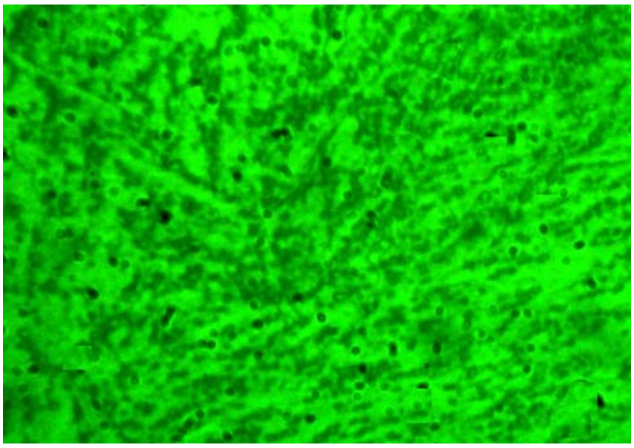

Fig. 2. X20CrMoV12.1 steel, structural rehabilitated state
[Etched HCl, 500x]

Experimental Program for Simulation of the Thermal Cycles

The experimental program for the thermal cycles simulation at welding of X20CrMoV12.1, structural and mechanical rehabilitated has many steps, but finally it can evaluate the possibility to weld this steel in the industrial practice (Figure 3).

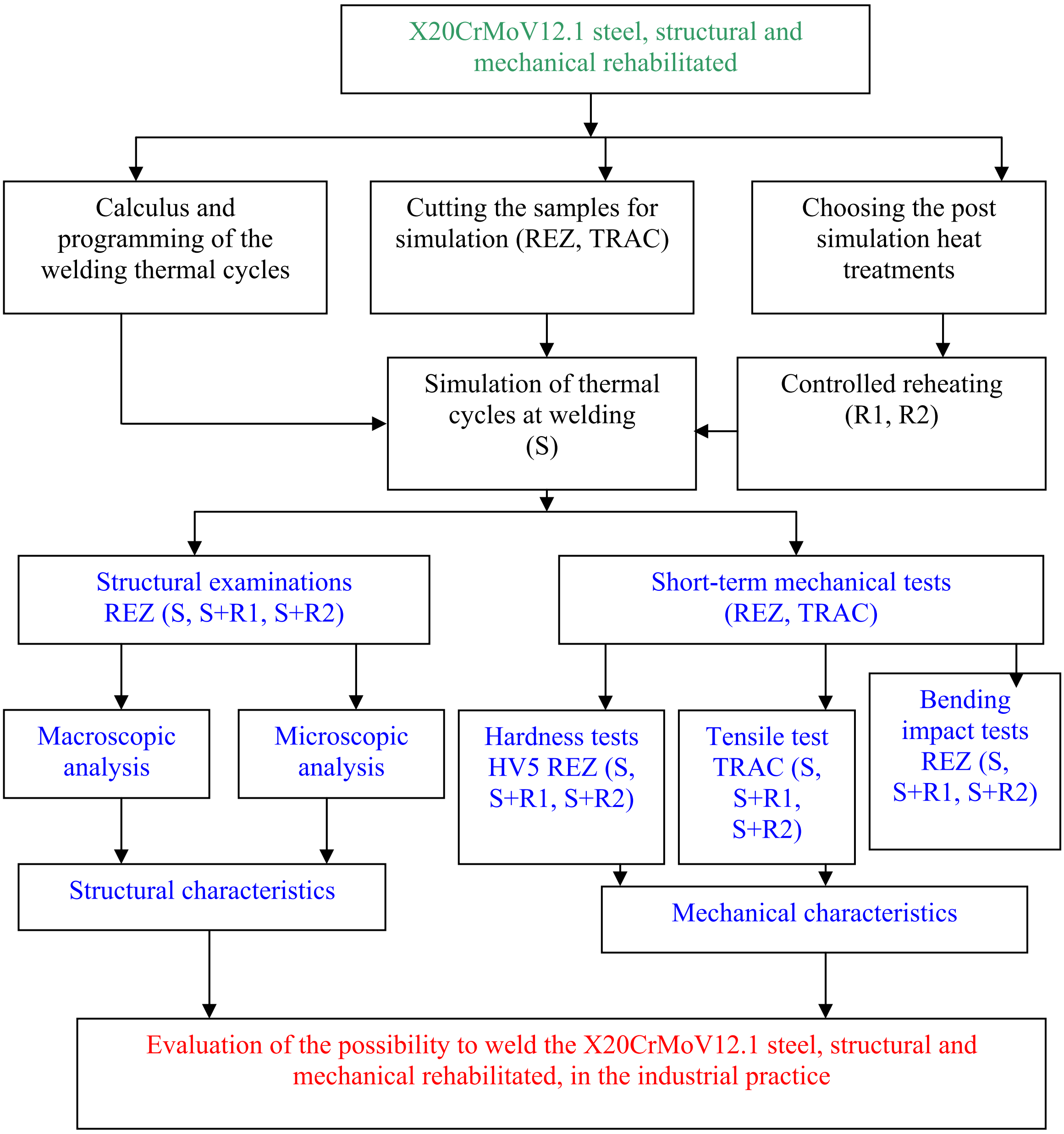

Fig. 3. The experimental program

Calculus and programming of the welding thermal cycles of the X20CrMoV12.1 steel were been made taking into consideration the technical data of the material characteristics, the welding parameters and the peak temperatures. It is mentioned the simulation variant with multiple peak temperatures Tv: 1350 °C + 1200 °C + 1000 °C, specific to welding steels in several layers with $t_{8/5}$ = 10 s, for each peak temperature, determined according to Rykalin's relations [4].

The samples preparation was made by cutting and processing the rehabilitated pipe, Ø 273 x 28 mm of REZ samples (11x11x55mm) and TRAC samples (Ø 5,5 x60 mm). The choice of the post-simulation heat treatment was based on the technical data regarding the thermal parameters of secondary treatment of X20CrMoV12.1 steel, referring to the high annealing (controlled reheating) in variants:

R1 – reheating at 750 °C/1h/ oven with $V_{heating} \approx V_{cooling} \approx 100$ °C/h;

R2 – reheating at 750 °C/1h/ air with the heating rate, specific to the heat treatment equipment (max. 400 °C/h).

The simulation of the welding thermal cycles was made using the Simulator for thermal cycles, type Smitweld LS – 1400 from ISIM Timisoara.

Macro- and Microscopic Examination of the Samples Subjected to Thermal Cycles at Welding

1. The macroscopic analysis made on the characteristics zones of the simulated samples (HAZ, BM) shows that HAZ increased on different distances with the values of 20 mm (S+R2), 20.46 mm (S) and 21.53 (S+R1). The macroscopic aspect of the simulated samples (S) and heat-treated samples (post-simulation) (S+R1, S+R2) are presented in figures 4; 5 and 6. The chemical etched was made with the reactive B8 according CR 12361+AC: 1999.

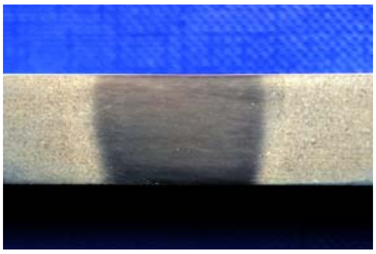

Fig. 4. S Sample (B8 Reactive)

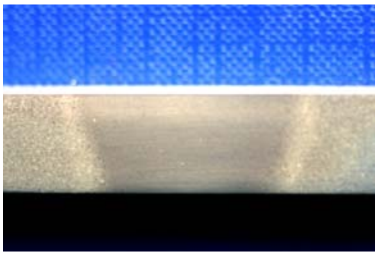

Fig. 5. S+R1 sample (B8 Reactive)

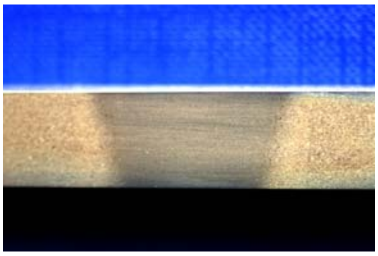

Fig. 6. S+R2 sample (B8 Reactive)

In the simulated zones, no cracks were been observed.

2. The microscopic analysis made according to EN 1321:2000 shows the next structures:
   - In the base materials (BM), ferrito-martensitic structures with complex carbides of Cr, Mo, (figures 7 and 8).

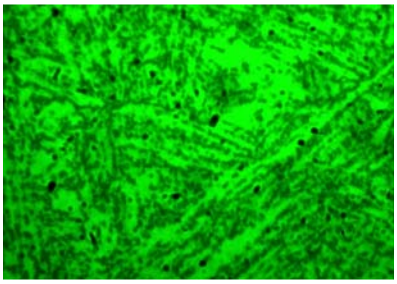

Fig. 7. BM. S sample [500 x]

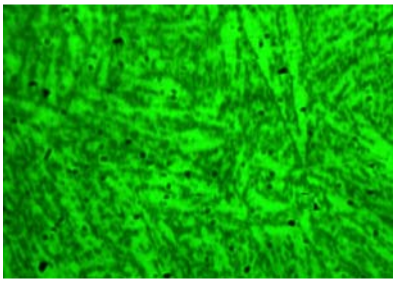

Fig. 8. BM. S+R1 sample [500x]

   - In the heat affected zones (HAZ) there are observed distinct phases and constituents with complex carbides of Cr, Mo, V, distributed:

- martensite and fine ferrite (figure 9) at S sample;
- annealed troostite, ferrite (figure 10) at S+R1 sample;
- fine annealed troostite with ferrite zones (figure 11) at S+R2 sample.

The metallographic zones present no microcracks.

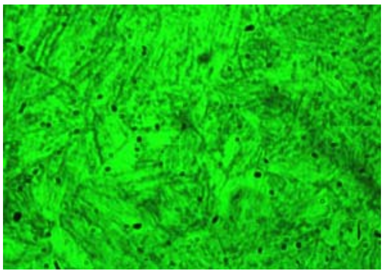

Fig. 9. S sample

[Etched HCl, 500x]

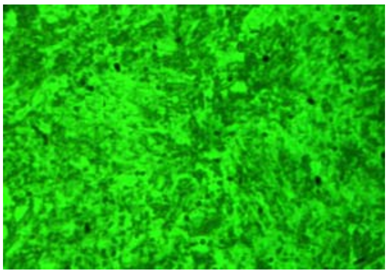

Fig. 10. S+R1 sample

[Etched HCl, 500x]

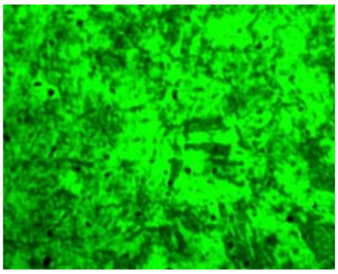

Fig. 11. S+R2 sample

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Short-term mechanical tests

1. HV5 hardness tests

HV5 hardness tests were made according to figures 12, with the constant measured step of 2 mm.

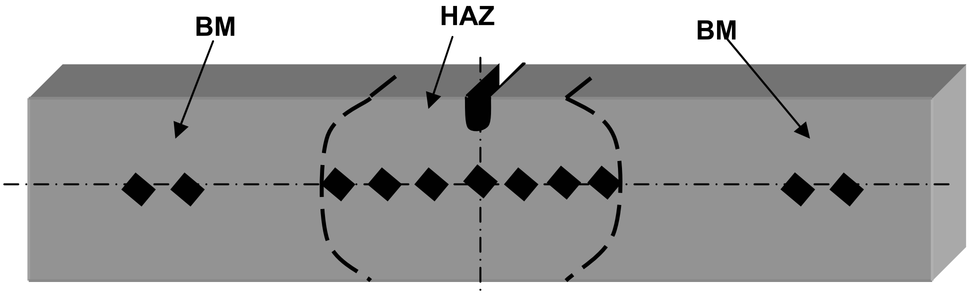

Fig. 12. The diagram of the hardness locations

The obtained hardness values are presented in the table 3. In this table, there are also inserted the local hardening estimator, ΔHV5 calculated with the relation:

$$\Delta HV5 = \frac{HV5\max - HV5\min}{HV5\max} 100\ [\%] \qquad (1)$$

where:

HV5max is HV5 maximum hardness determined in a zone;

HV5min is HV5 minimum hardness determined in another zone.

If ΔHV5 ≥ 50%, it is considered that the investigated zones presents a tendency to brittleness, with appearance of the local hardening [4].

Table 3. Hardness and hardening estimator values in the weld characteristics zones

Examined zone	**Analysed variant**	**HV5 hardness**		**ΔHV5 (HAZ) [%]**	**ΔHV5 (BM) [%]**
		Minimum val.	Maximum val.		
ZIT	S	412	566	27.42	-
	S+R1	310	362	14.36	-
	S+R2	306	362	15.46	-
MB	S	236	251	-	5.97
	S+R1	241	251	-	3.98
	S+R2	257	286	-	10.13

Analysing the ΔHV5 estimator, calculated in HAZ and BM, it is observed that the values are less than 50% (maximum 27.42% in HAZ and maximum 10.13% in BM), resulting that in the examined zones are not local hardness tendencies.

HV5 hardness variation function the distance in the characteristics zones (HAZ, BM) at the samples S, S+R1 and S+R2 is presented in the figure 13.

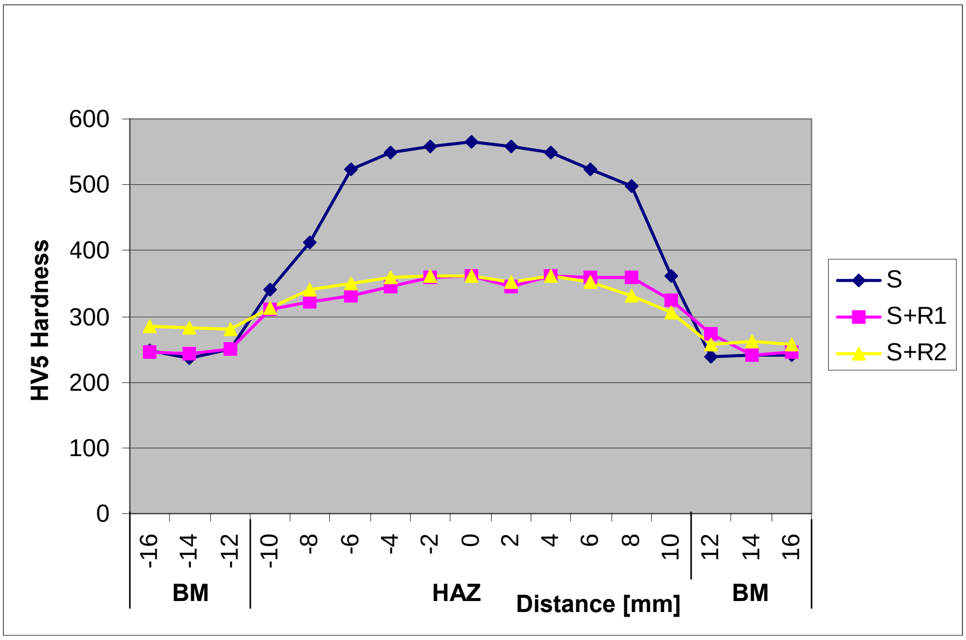

Fig. 13. HV5 hardness variation on the analyzed samples

Analyzing HV5 hardness variation function of the distance of the characteristics zones, it is observed that the maximum hardness (566 and 362) is in the middle of the heat-affected zone (HAZ), where the hard martensitic structures were been observed.

2. The impact bending test, made according to SR EN 875:1997, SR EN 10045-1:1993 and SR 13170:1993 on REZ samples (10x10x55mm) in S, S+R1 and S+R2 states, shows distinct values of the toughness characteristics in the heat affected zone and in the base material. These values are presented in the table 4.

Table 4. Toughness characteristics in the weld characteristics zones

Examined zone	**Fracture energy, KU [J]**		**Lateral expansion, LE [mm]**		**Crystallinity, Cr [%]**	
	Minimum value	Maximum value	Minimum value	Maximum value	Minimum value	Maximum value
0	1	2	3	4	5	6
HAZ (S)	8	16	0.01	0.36	95	100
HAZ (S+R1)	28	33	0.53	0.89	42	57
HAZ (S+R2)	34	49	0.59	0.79	41	48
MB rehabilitated state	63	81	1.19	1.78	44	65

The fracture energy variation (KU) and the lateral expansion function of the simulated variants are presented in figure 14.

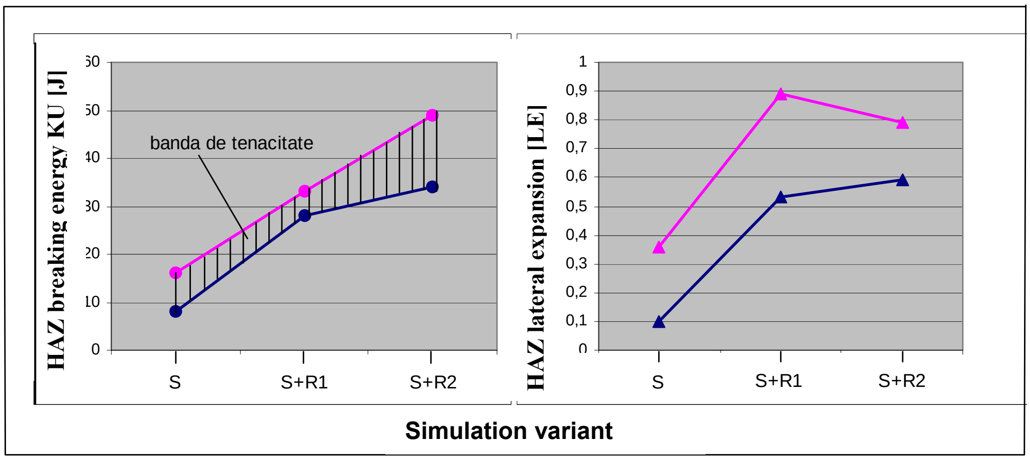

Fig. 14. KU and LE variation in HAZ = f (simulation variant)

Analyzing the fracture energy KU and the lateral expansion LE function the simulation, it is observed that at S+R2 variant, in HAZ are obtained high values of the fracture energy, higher than the minimum values of 34 J for BM where the lateral expansion has higher values between 0.50 and 0.79%, resulting that the toughness and the plastic deformation of the affected zones are adequately for the investigated steel and the brittle fracture risk is reduced.

3. Tensile test was made on simulated samples in the variants S, S+R1, S+R2 (dimensions Ø5x60mm). The experimental results are inserted in table 5.

Table 5. Mechanical characteristics of the simulated samples

Analyzed variant	**Yield strength, $Rp_{0.2}$ [N/mm^2]**		**Tensile strength, Rm [N/mm^2]**		**Elongation, A5 [%]**		**Reduction of area, Z [%]**	
	min	max	min	max	min	max	min	max
HAZ-(S)	-	-	1222	1238	-	-	-	-
HAZ-(S+R1)	951	984	1074	1111	6	9	51	54
HAZ-(S+R2)	920	944	1106	1146	13	16	54	54
BM – rehabilitated steel	570	593	752	787	20	21	54	54

In the figure 15 is presented the HAZ tensile strength, Rm, function of the applied simulated variants.

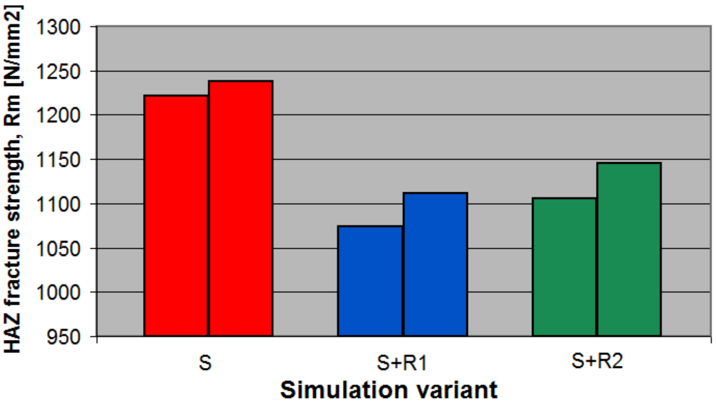

Fig. 15. HAZ variation, Rm= f(simulation variant)

Analyzing the histograms (figure 15), it is observed that both simulation variants (S+R1 and S+R2) satisfy the mechanical resistance characteristics of HAZ, because both variants exceed 752 N/mm^2 for the base metal, structural and mechanical rehabilitated (min. 1074 N/mm^2 at S+R1 variant, and min. 1106 N/mm^2 at S+R2 variant).

Conclusions

1. After the thermal cycles at welding with peak temperatures of Tv=1000°C + 1200°C + 1300°C, the alloyed steel X20CrMoV12.1 presents some structural transformations in the heat affected zone (HAZ), by developing the martensitic structures, which lead to the brittleness phenomena.
2. The mechanical characteristics of the heat-affected zone after simulation are modified, the tensile strength increased (between 1222 and 1238 N/mm^2), the toughness, KU is reduced to values between 8 and 16 J, with tendencies of brittle fracture appearance.
3. The application of the reheating thermal cycles in variants R1 and R2 leads to sorbite structures in HAZ, and higher toughness values of the fracture energy, KU between 18 and 33 J at S+R1 variant, and between 34 and 49 J, at S+R2 variant and higher fracture strength than the value of 840 N/mm^2 imposed for X20CrMoV12.1 steel (max. 1111 N/mm^2 at S+R variant, and max. 1146 N/mm^2 at S+R2 variant).
4. The structural characteristics correlated with the mechanical characteristics obtained in the affected zones by simulation cycles of the reheating treatments in variant R2 confirm the possibilities to weld the X20CrMoV12.1 steel, structural and mechanical rehabilitated, in the industrial practice.

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Simularea ciclurilor termice de la sudarea oțelului termorezistent aliat X20CrMoV12.1 reabilitat structural şi mecanic prin tratamente termice specifice

Rezumat

Oțelul termorezistent aliat sudabil marca X20CrMoV12.1 a lucrat pe un circuit termic la temperaturi şi presiuni ridicate (560 °C, 140 MPa) o perioadă îndelungată (98.000 ore), timp în care datorită modificărilor structurale, şi-a redus atât caracteristicile mecanice de rezistență, cât şi cele de tenacitate ale sudurii şi ale metalului de bază.

Reabilitarea structurală şi mecanică a acestui oțel s-a realizat prin aplicarea unor tratamente termice specifice (primare şi secundare) pentru refacerea caracteristicilor mecanice şi structurale la valori cât mai aproape de cele avute inițial în starea de livrare.

Evaluarea comportării metalurgice la sudare a acestui oțel a avut la bază simularea unor cicluri termice urmate de tratamente termice specifice, folosind epruvete prismatice de tip REZ (11x11x55mm) şi epruvete TRAC (Ø 5,5x60mm).

Prin analize metalografice (macro şi microscopice) şi prin încercări mecanice de scurtă durată (tracțiune, încercări de încovoiere prin şoc, duritate) efectuate atât pe epruvete simulate (S), cât şi pe epruvete simulate şi reîncălzite în două variante (S+R1, S+R2), s-au determinat principalele caracteristici structurale şi mecanice ale zonelor afectate de ciclurile termice de la sudare.

În final, s-au atestat posibilitățile de sudare în practica industrială a acestui oțel reabilitat structural şi mecanic.