

An Analysis of Transition Temperature for Real and Simulated Heat Affected Zone of HSLA Steel

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Abstract: The aim of this paper is to present the analysis of the influence of different test temperatures on the impact toughness of the real heat affected zone (RHAZ) and the simulated heat affected zone of the welded joint (SHAZ) of high strength low-alloy steel. Through thermal cycle simulation, which includes heating to a certain temperature and programmed cooling, the microstructure of different areas of the heat-affected zone was obtained on the samples, which allows us to directly draw appropriate conclusions regarding the real heat-affected zone of the welded joint. Based on the previous text, a comparison of the brittleness transition temperature values for RHAZ and SHAZ as a very important factor for structural steels was made. It has been observed that with a decrease in temperature many metals exhibit a sudden decrease in toughness, so the temperature at which the material transits from ductile to brittle fracture is called brittle transition temperature (ductile-brittle transition temperature). This indicator is very important regarding further design and exploitation of welded steel structures.

Keywords: HSLA; impact toughness; Nionikral 70; simulated heat affected zone (SHAZ); transition temperature

1 INTRODUCTION

The analysis of impact tests is crucial because these tests replicate the ductile-brittle transition of steel within a temperature range that closely mimics real-world conditions for welded structures. The ductile-brittle transition temperature is particularly important, as it plays a significant role in the failure mechanisms of materials, with many historical incidents of failures and damages attributed to this phenomenon. Test results evaluating the toughness of high strength low-alloy steels at varying temperatures demonstrate that temperature has a considerable effect on the impact toughness of both steels and their alloys, with lower temperatures typically leading to reduced toughness and a greater likelihood of brittle fracture. The test results of high-strength low-alloy steel toughness assessments at various temperatures clearly indicate that temperature has a significant impact on the material's impact toughness. As the temperature decreases, the steel's ability to absorb energy during impact typically decreases as well, making the material more prone to brittle fracture. This highlights the importance of considering temperature effects when evaluating the performance and reliability of steels and their alloys in real-world applications, particularly in environments subject to varying or low temperatures.

The transition temperature is a critical factor for steel welded joints, as it marks the temperature at which the material shifts from ductile behaviour to brittle fracture. This phenomenon is particularly significant because many metals exhibit a sharp decrease in toughness as the temperature drops, making them more susceptible to brittle failure. The temperature at which this transition occurs is known as the ductile-brittle transition temperature. It is defined as the inflection point on the total impact energy-temperature curve, where the material's ability to absorb impact energy significantly declines [1]. The ductile-brittle transition temperature is influenced by several factors, including the chemical composition, microstructure, grain size, surface roughness, specimen shape, and notch depth. These factors can either raise or lower the transition temperature, affecting the material's performance under different temperature conditions. Understanding and

accurately determining the transition temperature is essential for designing welded structures that will perform reliably under various operating temperatures, especially in critical applications where material failure could have serious consequences [1].

Welding is, due to the high speed of heating and cooling, an unbalanced process where all phase and structural changes that take place during welding occur in conditions under which overheating or undercooling are carried out. During fusion welding of steel, a whole series of elementary and complex processes which cause the appearance of differences in the composition, structure and level of stresses present in the constituent parts of the welded joint, the weld metal (WM) and the heat affected zone (HAZ) in relation to the parent metal (PM) takes place [2]. The mechanical and technological properties of the welded joint depend both on the properties of the weld metal and on the properties of the heat-affected zone and the parent metal. These properties depend on the structure of individual sections of the welded joint, by the chemical composition, welding thermal cycle and post weld heat treatment. The procedure and mode of welding significantly affect the properties of the weld metal, since the structure and chemical composition of the weld metal depend on them. The quantity of base metal within the weld metal depends on the applied procedure and mode of welding, and this ratio can vary from 15-80% [3]. When welding in multiple passes is being performed, the weld metal is exposed to the reverse action of the welding thermal cycle and therefore it has a more favourable fine-grained structure. As a result, the weld metal of multi-pass seams has a lower transition temperature and better plasticity properties.

When it comes to the properties of the welded joint, a much more significant problem is the change in the metallurgical and technological properties in the heat-affected zone or, to be more precise, the decrease in plasticity in the heat-affected zone. The structure and properties of the parent metal in the heat-affected zone depend on the chemical composition of the parent metal and on the welding thermal cycle. The basic parameters of the thermal cycle of the heat-affected zone are: maximum heating temperature, heating speed through the

temperature range between 700 °C and 1000 °C, cooling speed through the temperature range between 800 °C and 500 °C, heating time from A_{c3} to maximum temperature, cooling time from maximum temperature to A_{r3} [4]. The width and final structure of different sections of the zone subjected to the influence of heat is determined by the welding method and welding mode, as well as by the composition and thickness of the parent metal (Fig. 1a and 1b). Transformations in the heat-affected zone are taking place under conditions of continuous temperature changes, strains and stresses due to uneven heating and cooling of metal during welding [3, 5]. Therefore, one of the main difficulties in welding high-strength low-alloy steels is the appearance of a drop in plasticity and toughness in the heat-affected zone, which results in the appearance of cracks. Therefore, obtaining a quality welded joint of high-

strength steel with a good knowledge of all the structures and intermediate structures of the heat-affected zone and their influence on the properties of the welded joint is a very complex issue.

Determination of the critical properties of HAZ is complex due to the difficulty to define the position of the critical microstructure and to locate the tip of the notch or crack, therefore the determination of the local behaviour parameters of the metal, such as the fracture toughness, is rather difficult. Through thermal cycle simulation, which was carried out by heating to a certain temperature and programmed cooling, the microstructure of different areas of the HAZ, (SHAZ - simulated HAZ) was obtained on the samples, which facilitates this test and enables direct drawing of appropriate conclusions for the real HAZ of a welded joint [6].

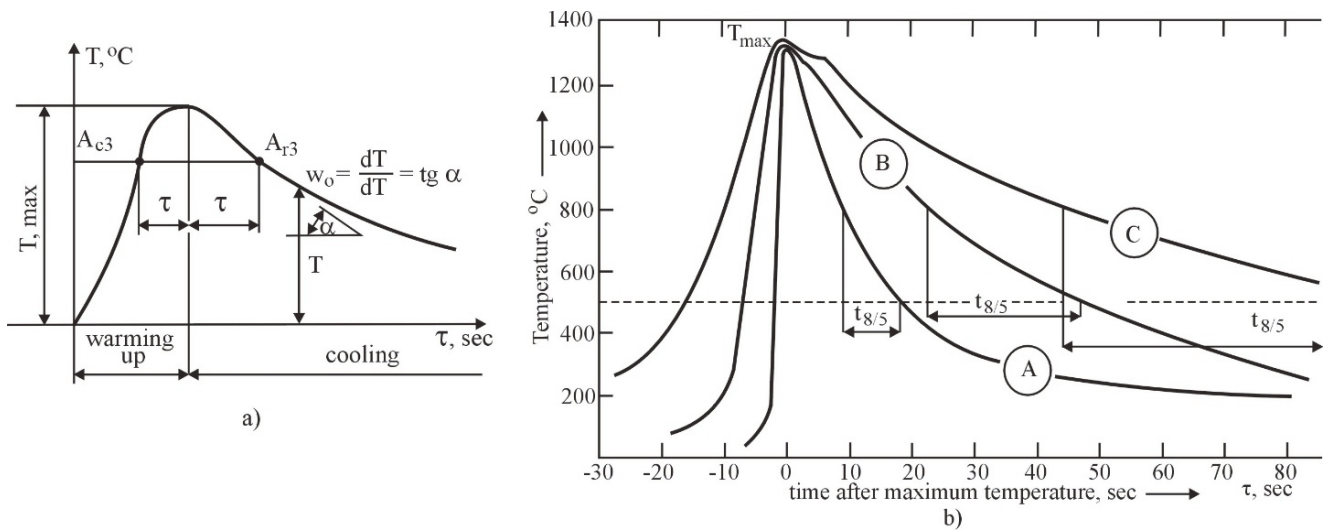


Figure 1 Chart of the thermal cycle of HAZ for arc welding (1a) and for different welding processes (1b) [3, 5]

2 THERMAL CYCLE SIMULATION OF THE HEAT AFFECTED ZONE

A simulated heat affected zone (SHAZ) can be obtained by heating samples to a previously set temperature in a furnace or on a thermomechanical welding simulator. A welding simulator is a device that achieves controlled heating and cooling, similar to what occurs during welding. Depending on which tests are required (impact, tensile or fatigue tests), a microstructure of about 10 mm width is obtained in the middle section of the sample, which corresponds to the HAZ and therefore enables determination of its mechanical properties [7].

Input of parameters was carried out via a computer, and the basis for parameter selection can be the calculation of the temperature field, as well as the use of appropriate equations for calculating $\Delta t_{8/5}$ in the welding thermal cycle. Thermal cycles on the welding simulator were achieved by electric resistance heating, according to a given time plan and were controlled by a photocell simply by following a given cooling curve, Fig. 2. A predetermined and adjusted heating current was passed through the test specimen until the test tube was heated to the maximum temperature. The jaws in which the sample was located were cooled by water, while the sample itself was cooled by a jet of inert gas or a jet of carbon dioxide [8, 9].

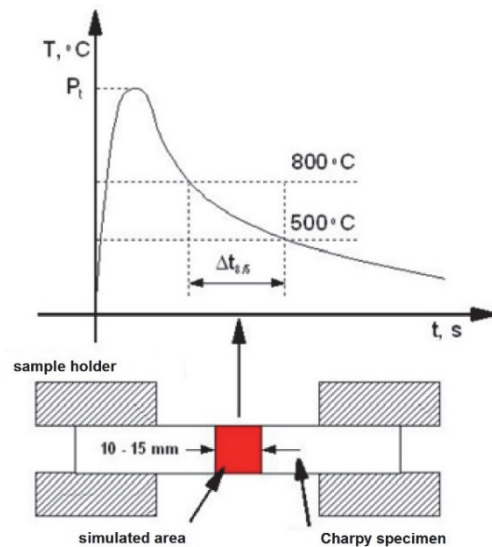


Figure 2 Display of HAZ simulation [8]

Due to the heterogeneity of the structure and properties of the welded joint, it was not easy to directly apply the test results of the simulated samples to the welded joint, especially taking into account the fact that in real welded joints subsequent phase transformations occur during the second and subsequent passes. When it comes to multi-pass welding, the overlapping of thermal cycles

refines the microstructure of the HAZ, which is manifested by the absence of local brittle zones. However, this overlap can cause such a combination of thermal cycles that create new martensitic-austenitic constituents. This means that, when it comes to multi-pass welding, in addition to heat input, the combination of heat cycles is also very important, so heat input recommendations should be based on tests performed on simulated samples [10].

The microstructure of the simulated sample and the corresponding microstructure in the HAZ could be taken as a basis for comparison, and the results obtained for simulated samples can be attributed to that area of the HAZ [10, 11]. Grains close to the fusion line can be expected to be finer in a real weld than in a simulated weld sample, where there is no reheating [10]. Despite their obvious advantages, impact tests performed on the simulated heat-affected zone cannot replace impact tests performed on the HAZ of a real welded joint. When it comes to the impact tests performed on the simulated heat-affected zone, they cannot replace the impact tests performed on the real HAZ, but, in general, tests performed on simulated test specimens should be combined with standard mechanical tests.

3 EXPERIMENTAL PROCEDURE

Structural components made by welding of high strength low-alloy steel (HSLA) in order to be as light as possible and increase the load capacity, especially when it comes to the welded joint, which is, along with its constituents (PM, HAZ and WM), the weakest area, need to be able to withstand complex variable loads. The high strength low-alloy steel Nionikral NN-70, which contains the following elements in the following percentages, was tested: C 0,106%, Si 0,209%, Mn 0,220%, P 0,005%, S 0,0172%, Cr 1,258%, Ni 2,361%, Mo 0,305%, V 0,052%, Sn 0,014%, Cu 0,246%, Ti 0,002%, Nb 0,007%, Co 0,0189% [12]. High-strength low-alloy steels are designed to offer a combination of high strength and excellent mechanical properties, but they must also possess several other key characteristics. In addition to their primary strength, HSLA steels should exhibit exceptional plasticity, which allows them to deform without breaking under stress. Adequate toughness is another critical property, ensuring the material can absorb energy without fracturing, particularly under impact or stress conditions.

Moreover, HSLA steels should have high resistance to brittle fracture, especially at low temperatures, where materials are more prone to sudden failure. This is particularly important for applications in harsh environments where temperatures can fluctuate. Workability is also essential, as the steel should be easily shaped and processed during manufacturing. Lastly, good welding performance is crucial, as HSLA steels are often used in welded structures, and poor weldability can lead to defects and reduced structural integrity.

In summary, HSLA steels are valued not only for their strength but also for their ability to maintain high toughness, plasticity, and durability, while being suitable for welding and fabrication processes. These properties make them ideal for use in demanding applications like construction, automotive, and structural engineering, where both strength and reliability are critical.

Therefore, this paper presents the determination of the ductile-brittle transition temperature for real heat affected zone (RHAZ) and the simulated heat affected zone (SHAZ) of the NN-70 welded joint and the comparison of acquired results, all with the aim of determining the ductile-brittle transition temperature as an important parameter obtained by impact tests at different temperatures. As there are several ways of determining the transition or critical temperature, the 27 J criterion was used in this experiment. It is the temperature at which the total impact energy is 27 J [1]. Before constructing the force-time (energy-time) diagram in order to determine the total impact energy, the test specimens of SHAZ and RHAZ were prepared for testing. The microstructure of HAZ steel NN-70 needed for impact tests (selection of the simulation mode and determination of transition temperature for the selected simulation mode) was simulated on a SmithWeld type simulator (Thermal Cycle Simulator Tensile Test Unit - SmithWeld, model 1405). Samples with dimensions of $11 \times 11 \times 60$ mm were exposed for 0,5 s to an austenitizing temperature of 1300 °C and subjected to different cooling times $\Delta t_{8/5} = 8, 10, 20$ and 40 s in order to obtain the structure and properties of the SHAZ material that approximately correspond to the structure and material properties of the real HAZ steel NN-70, which was determined by impact and hardness tests, as well as tests performed with the aim to determine the structure of the material [13, 14].

After the selected simulation mode $\Delta t_{8/5} = 40$ s, which approximately corresponds to the cooling time $\Delta t_{8/5}$ RHAZ, the samples with dimensions of $11 \times 11 \times 60$ mm were exposed for 0,5 s to the austenitizing temperature of 1300 °C in order to determine the transition temperature. For the adopted simulation mode, $\Delta t_{8/5} = 40$ s, 13 specimens were made for impact testing in order to determine the ductile-brittle transition temperature of SHAZ, Fig. 3, after the simulation.

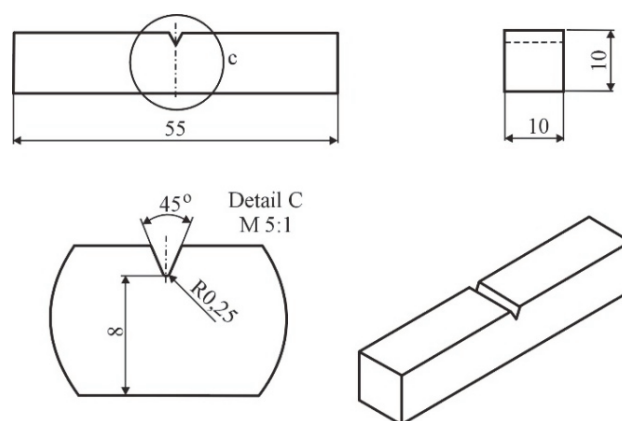


Figure 3 Impact test specimen on an instrumented pendulum with an oscilloscope Schenck Trebel [13]

Also, at the same time when the SHAZ test specimens were made, a total of 9 test specimens were taken from the sample of RHAZ real welded joint NN-70. SHAZ was tested at temperatures of 20 °C, -20 °C, -40 °C and -60 °C, while RHAZ was tested at 20 °C, -40 °C and -80 °C [15].

The test procedure, as well as the specimen sizes and shapes, are specified according to SRPS EN 10045-1 and SRPS EN 10045-2, or ASTM E23-02 [16-19]. These

standards define the requirements for conducting impact tests, ensuring consistency and reliability in the results. Impact testing is performed using the SCHENCK TREBEL 150-300 J instrumented Charpy pendulum, which allows for precise measurement of the material's impact energy absorption at various temperatures. Using instrumented Charpy pendulum, more precisely by installing a device that records the change of force and energy with the test time, significant progress was made in the development of impact toughness testing. The results of the test on the instrumented Charpy pendulum allow complete monitoring and understanding of the fracture mechanism and the separation of the total impact energy into the crack initiation energy and crack propagation energy. The position of the notch on the impact test specimen is determined according to EN 875 [20], which provides guidelines on specimen preparation and notch placement for accurate and consistent testing results. During the impact testing process using the SCHENCK TREBEL instrument, force-time diagrams are generated [15], which help to visualize the dynamic response of the material under impact. These diagrams are essential for determining the total impact energy absorbed by the specimen during testing.

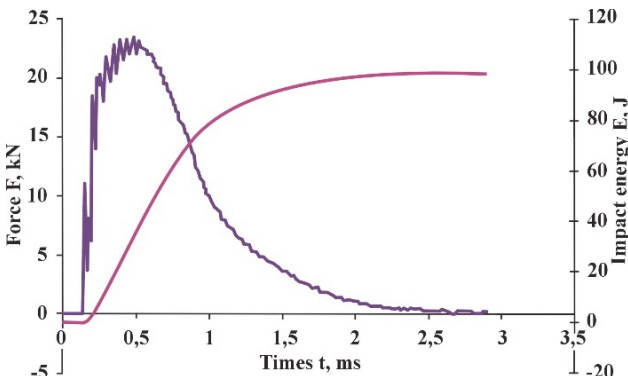


Figure 4 Diagram of force-time and energy-time for RHAZ of NN-70 at -40 °C [15]

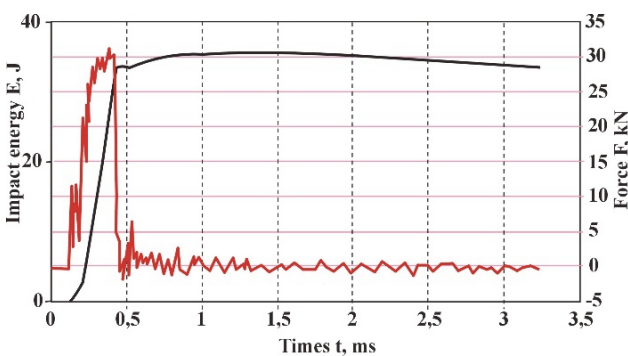


Figure 5 Diagram of force-time and energy-time SHAZ of NN-70 at -60 °C [13]

Figs. 4 and 5 present the force-time and energy-time curves for the material NN-70, showing the behaviour of the steel at different temperatures. The RHAZ and SHAZ diagrams of NN-70 at temperatures of -40 °C and -60 °C respectively, provide insight into the material's response to impact at low temperatures. By analysing the force-time and energy-time diagrams, engineers can determine the material's impact toughness, identify temperature-dependent changes in behaviour, and assess its suitability for use in environments where low-temperature performance is critical.

Total impact energy results for heat-affected zone of NN-70 are in Tab. 1 and total impact energy results for simulated heat-affected zone of NN-70 are in Tab. 2, with their mean values.

Table 1 Total impact energies of RHAZ of NN-70 at different temperatures

Specimen	Temperature / °C	Total impact energy / J	Mean values of total impact energies / J
RHAZ 1	20	104,88	111,58
RHAZ 2	20	109,67	
RHAZ 3	20	120,18	
RHAZ 4	-20	98,59	104,58
RHAZ 5	-20	106,79	
RHAZ 6	-20	108,35	
RHAZ 7	-80	51,34	50,57
RHAZ 8	-80	87,02	
RHAZ 9	-80	13,36	

Table 2 Total impact energies of SHAZ of NN-70 at different temperatures

Specimen	Temperature / °C	Total impact energy / J	Mean values of total impact energies / J
SHAZ 1	20	53,8	62,95
SHAZ 2	20	62,21	
SHAZ 3	20	68,71	
SHAZ 4	20	67,08	46,17
SHAZ 5	-20	45,29	
SHAZ 6	-20	48,47	
SHAZ 7	-20	44,76	38,28
SHAZ 8	-40	34,98	
SHAZ 9	-40	40,37	
SHAZ 10	-40	39,5	32,10
SHAZ 11	-60	33,59	
SHAZ 12	-60	27,05	
SHAZ 13	-60	35,67	

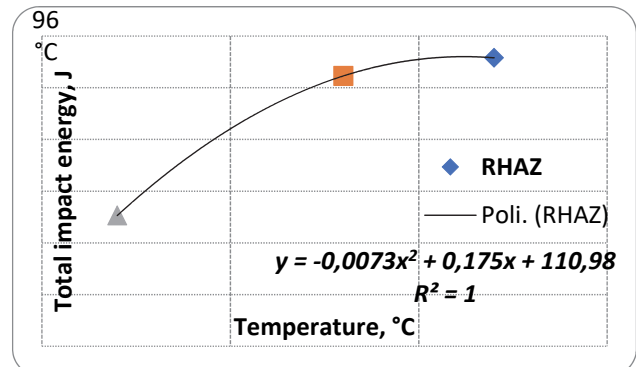


Figure 6 Dependence of the test temperature and the total impact energy for RHAZ

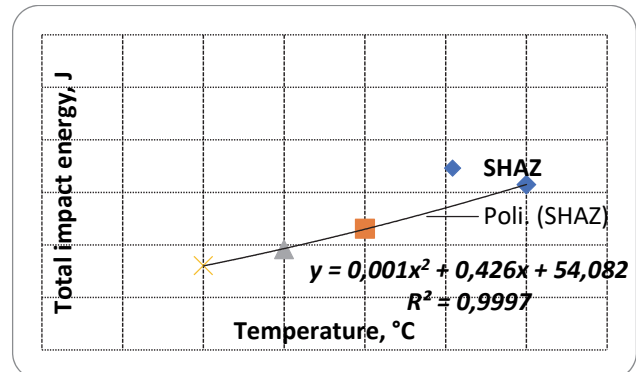


Figure 7 Dependence of the test temperature and the total impact energy for SHAZ

A polynomial of the dependence of the test temperature and the total impact energy was constructed for RHAZ and SHAZ (Fig. 6 and Fig. 7) by using mean values of the total impact energy.

A curve that was constructed based on the obtained polynomial dependence of temperature and total impact energy for RHAZ and SHAZ in order to determine the transitional temperature for impact energy of 27 J is shown in Figs. 8 and Fig. 9. Tabs. 3 and 4 were derived from those curves. Also, Tabs. 3 and 4 show the impact energy that is the closest to the impact energy of 27 J (bold values) and thus defines the transition temperature.

Table 3 Values of the polynomial for constructing the dependence curve of temperature and total impact energy for RHAZ

Polynomial		Mean values of total impact energies for RHAZ / J
$Y = -0,00073x^2 + 0,175x + 110,98$	-180	-157,04
	-170	-129,74
	-160	-103,90
	-150	-79,52
	-140	-56,60
	-130	-35,14
	-120	-15,14
	-110	3,40
	-97	25,32
	-96	26,90
	-95	28,47
	-86	41,94
	-77	54,22
	-67	66,49
	-57	77,29
	-47	86,63
	-37	94,51
	-27	100,93
	-17	105,90
	-7	109,40
3	111,44	
13	112,02	
23	111,14	
33	108,81	

Table 4 Values of the polynomial for constructing the dependence curve of temperature and total impact energy for SHAZ

Polynomial		Mean values of total impact energies for SHAZ / J
$Y = 0,001x^2 + 0,426x + 54,082$	-180	9,80
	-170	10,56
	-160	11,52
	-150	12,68
	-140	14,04
	-130	15,60
	-120	17,36
	-110	19,32
	-100	21,48
	-90	23,84
	-79	26,67
	-78	26,94
	-77	27,21
	-68	29,4
	-58	32,74
	-48	35,94
	-38	39,34
	-28	42,94
	-18	46,74
	-8	50,74
2	54,94	
12	59,34	
22	63,94	
32	68,74	

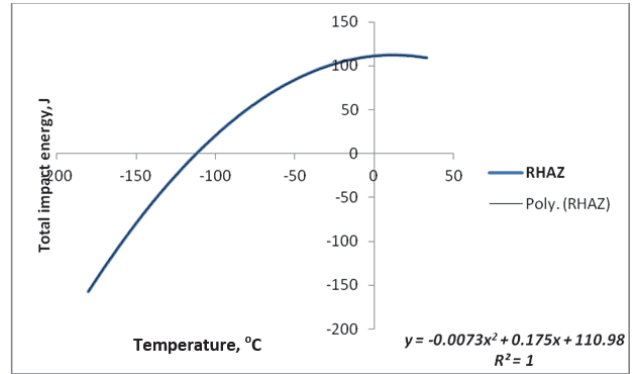


Figure 8 Curve of dependence of temperature and total impact energy constructed on the basis of obtained polynomial dependence of temperature and total impact energy for RHAZ

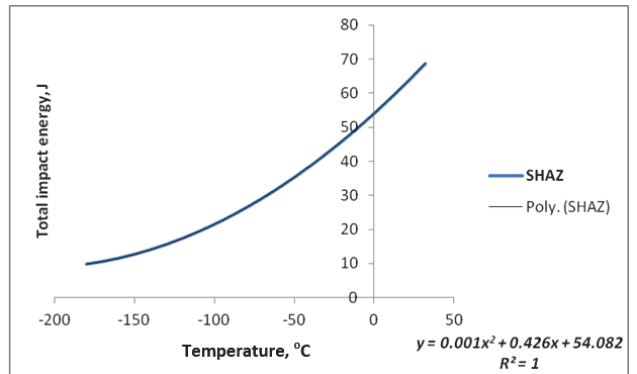


Figure 9 Curve of dependence of temperature and total impact energy constructed on the basis of obtained polynomial dependence of temperature and total impact energy for SHAZ

Fig. 10 comprises the curves that show the dependence of the total impact energy and temperature for RHAZ and SHAZ, where the ductile-brittle transition temperature values for the real and simulated HAZ for the total energy values of approximately 27 J are clearly visible. Tab. 3 contains the values of the transition temperature.

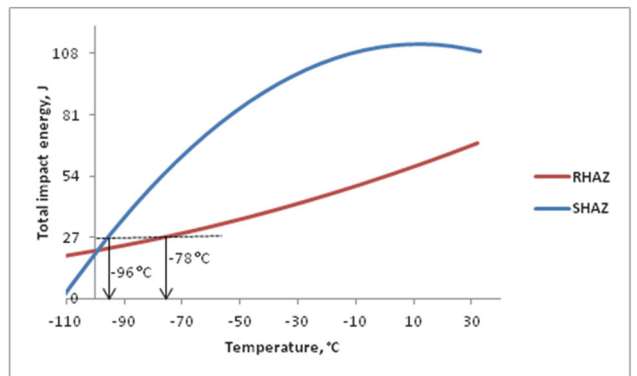


Figure 10 Notch total impact energy as a function of temperature for RHAZ and SHAZ

Table 3 Transition temperature values for RHAZ and SHAZ of NN-70

Criterion for determining the transitional temperature for an impact energy of 27 J through defined polynomials		
	RHAZ	SHAZ
Total impact energy / J	26,90	26,94
Transition temperature / °C	-96	-78

4 CONCLUSION

A polynomial dependence of the change in total impact energy and test temperature was established for RHAZ and SHAZ, using the 27 J criterion, which is currently one of the most common criterions for determination of the transition temperature.

Through analysis of the diagrams shown and the results obtained for the real HAZ and simulated HAZ of NN-70 steel, i.e. comparing the ductile-brittle transition temperature values of $-96\text{ }^{\circ}\text{C}$ for the real HAZ and $-78\text{ }^{\circ}\text{C}$ for the simulated HAZ, it can be concluded that the SHAZ samples have a homogeneous structure through which the resulting crack forms brittle fracture at a higher temperature ($-78\text{ }^{\circ}\text{C}$), while the crack in the RHAZ partially grows and shows better toughness up to temperature ($-96\text{ }^{\circ}\text{C}$), which means that the result of testing SHAZ samples is conservative, on the side of safety and can be considered and applied when designing real welded structures, which reduces the costs of RHAZ testing.

More precisely, the samples taken from the real HAZ have a higher resistance to the transition to the brittle state than the samples taken from the simulated HAZ, or, to put it a bit differently, to the transition from the ductile to the brittle state.

Although the impact tests of the simulated heat-affected zone can replace the HAZ impact tests performed on specimens taken from the samples of the real welded joints, for a more precise determination of the transition temperatures, tests performed on simulated test specimens should be combined with standard mechanical tests in order to define the metallurgical and technological properties of the welded joint in terms of changes in the heat-affected zone better, i.e. drop of plasticity in the heat-affected zone.

Acknowledgment

This research is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contract No. 451-03-66/2024-03/200012).

5 REFERENCES

- [1] Bulatović, S., Aleksić, V., Milović, Lj., Zečević, B., & Milović, Lj. (2021). An analysis of impact testing of high strength low-alloy steels used in ship construction. *Brodogradnja*, 72(3), 1-12. <https://doi.org/10.21278/brod72301>
- [2] Vidojević, N. (2000). The structural changes near the weld metal in fusion welding of steel. *Welding & welded structures*, 45(3), 115-118.
- [3] Grabulov, V. (1986). *Prilog definisanju uticaja hemijskog sastava i debljine lima na pojavu prskotina u zavarenim spojevima čelika Nionikral-70*. Master dissertation.
- [4] Samarardžić, I., Dunder, M., & Vuherer, T. (2015). Dependence of hardness and impact energy on cooling time $\Delta t_{8/5}$ and temperature for S960QL. *Metalurgija*, 54(2), 403-406.
- [5] Hrivnjak, I. (1992). *Theory of weldability of metals and alloys*. Department of Materials Science, Faculty of Metallurgy, Technical University, Kosice.
- [6] Harrison, J. D. & Anderson, T. L. (1985). The application of fracture mechanics to welded construction. *Eighteen ASTM National Symposium on Fracture Mechanics*, 1-16.

- [7] Momčilović, D. (2000). *Ispitivanje otpornosti na nastanak i rast prslina čelika 12H1MF pri dejstvu udarnog opterećenja*. Master dissertation.
- [8] Milović, Lj. (20008). *Analiza integriteta zavarenih komponenta procesne opreme za povišene radne temperature*. Doctoral dissertation.
- [9] Samarardžić, I., Čorić, A., & Dunder, M. (2016). Weldability investigation of fine-grained s1100ql steel. *Metalurgija*, 55(3), 453-456.
- [10] Gerić, K. & Sedmak, S. (2000). Crack resistance of the heat-affected-zone of microalloyed steels. *Welding & welded structures*, 45(2), 59-62.
- [11] Adžijev, G., Sedmak, A., Gliha, V., & Vuherer, T. (2003). Welding thermal cycles influence on microalloyed steel haz toughness. *Welding & welded structures*, 48(3), 144-147.
- [12] Bulatović, S., Aleksić, V., Milović, Lj., & Zečević, B. (2023). Experimental Determination of the Critical Value of the J-Integral that Refers to the HSLA Steel Welded Joint. *Technical Gazette*, 30(1), 1148-152. <https://doi.org/10.17559/TV-20220419093052>
- [13] Aleksić, V. (2019). *Low cycle fatigue of high strength low alloy steels*. Doctoral dissertation.
- [14] Dunder, M., Samarardžić, I., & Vuherer, T. (2015). Weldability investigation steel P 91 by weld thermal cycle simulation. *Metalurgija*, 54(3), 539-542.
- [15] Bulatović, S., Aleksić, V., & Mladenović, M. (2023). Influence of temperature on impact toughness of HSLA steels. *Structural Integrity and Life*, 23, S91-S94.
- [16] SRPS EN 10045-1 (1993). Mehanička ispitivanja metala - ispitivanje udarom po Šarpiju, Deo 1: Metoda ispitivanja, (in Serbian) (Metallic materials - Charpy impact test - Part 1: Test method).
- [17] SRPS EN 10045-2 (1993). Mehanička ispitivanja metala - ispitivanje udarom po Šarpiju, Deo 2: Verifikacija uređaja za ispitivanje, (in Serbian) (Metallic materials - Charpy impact test - Part 2: Verification of test method).
- [18] ASTM E 23-02 (2002). Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, Annual Book of ASTM Standards, Vol. 03.01.
- [19] Bukvić, A., Burzić, Z., Prokić-Cvetković, R., Popović, O., Burzić, M., & Jovičić, R. (2012). Welding technology selection effect on fracture-toughness parameters of bi-material welded joints. *Technical Gazette*, 19(1), 167-174.
- [20] EN 875 (1995) Destructive tests on welds in metallic materials - Impact tests - Test specimen location, notch orientation and examination. CEN/TC 121.

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