Ivica Čamagić[1], Srđan Jović[1], Mladen Radojković[2], Simon Sedmak[3], Aleksandar Sedmak[4], Zijah Burzić[5], Cristian Delamarian[6]

INFLUENCE OF TEMPERATURE AND EXPLOITATION PERIOD ON THE BEHAVIOUR OF A WELDED JOINT SUBJECTED TO IMPACT LOADING

UTICAJ TEMPERATURE I VREMENA EKSPLOATACIJE NA PONAŠANJE ZAVARENOG SPOJA PRI DELOVANJU UDARNOG OPTEREĆENJA

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.169.1:669.15`26`28
Rad primljen / Paper received: 20.12.2016

Adresa autora / Author's address:
1) University of Priština, Faculty of Tech. Sciences, Kosovska Mitrovica, Serbia, ivica.camagic@pr.ac.rs
2) High Technical School of Professional Studies, Zvečan, Serbia
3) University of Belgrade, Innovation Centre of the Faculty of Mech. Engng., Belgrade, Serbia
4) University of Belgrade, Faculty of Mech. Engng., Serbia
5) Military-Technical Institute, Belgrade, Serbia
6) TUV SUD Romania S.R.L, Bucarest, Romania

Keywords
- welded joint
- notch
- crack initiation energy
- crack propagation energy
- instrumentation

Abstract

Presented in this paper is the analysis of the influence of temperature and exploitation period on the measure of fracture resistance of welded joint constituents in both new and exploited low-alloyed Cr-Mo steel A-387 Gr. B subjected to impact load. Exploited parent material was a part of the reactor mantle in exploitation for over 40 years and is currently in the repair stage, wherein a part of the mantle is being replaced with newly built-in material. Performed are impact tests of a notched specimen of new and exploited parent material (PM), weld metal (WM) and heat affected zone (HAZ), at both the exploited and new PM sides, in order to determine total impact energy, and its components, crack initiation- and crack propagation energy. Based on test results, analysis of tendency toward brittle fracture, i.e. toward an increase of in-service brittleness (ageing) represents the comparison of values obtained for characteristic areas of welded joints and the justification of the selected welding technology.

Ključne reči
- zavareni spoj
- zarez
- energija stvaranja prsline
- energija širenja prsline
- instrumentiranje

Izvod

U ovom radu je prikazana analiza uticaja vremena eksploatacije i temperature na meru otpornosti na lom konstituenata zavarenog spoja novog i eksploatisanog niskolegiranog Cr-Mo čelika A-387 Gr. B pri delovanju udarnog opterećenja. Eksploatisani osnovni metal je deo plašta reaktora koji je bio u eksploataciji preko 40 godina i u fazi sanacije oštećenja, odnosno, zamene dela plašta novougrađenim materijalom. Udarna ispitivanja epruveta sa zarezom u novom i eksploatisanom osnovnom metalu (OM), metalu šava (MŠ) i zoni uticaja toplote (ZUT), sa strane eksploatisanog OM i sa strane novog OM, su rađena u cilju određivanja ukupne energije udara, kao i komponenata, energije stvaranja - i energije širenja prsline. Na osnovu rezultata ispitivanja, analiza sklonosti ka krtom lomu, odnosno, sklonosti ka povećanju krtosti u toku eksploatacije (starenje) predstavlja poređenje dobijenih vrednosti za karakteristične oblasti zavarenog spoja i opravdanost izabrane tehnologije zavarivanja.

INTRODUCTION

A long exploitation period for a pressure vessel-reactor (over 40 years) causes certain damages to the reactor mantle. The occurrence of this damage requires a very thorough inspection of the reactor structure itself, along with the repair of damaged parts. Reparation of the reactor involved the replacement of a part of the mantle with newly built-in material. The pressure vessel in question is of low-alloyed steel Cr-Mo A-387 Gr. B in accordance with the ASTM standard, with (0.8-1.15)% Cr and (0.45-0.6)% Mo. In the case of design working parameters (p = 35 bar and t = 537°C), the material lies in the area with a tendency towards de-carbonisation of the surface in contact with hydrogen. Reduced material strength may result as a consequence of surface de-carbonisation. In terms of structure, the reactor represents a vertical pressure vessel with a cylindrical mantle. Deep lids are welded onto both the upper and lower side of the mantle, of the same quality as the mantle. Within the reactor, the most important process in motor oil production stage takes place which involves the platforming for altering the structure of hydrocarbon compounds and achieving of a higher octane number. Testing of the new and exploited parent materials (PM), along with welded joint components (weld metal-WM and heat affected zone-HAZ), of a low-alloyed steel of the reactor, included determining impact properties of the exploited and new PM and welded joint components at room and working temperature of 540°C, using an instrumented Charpy pendulum, /1/.

MATERIAL

Exploited PM is steel A-387 Gr. B with a thickness of 102 mm, whereas the new PM is also steel A-387 Gr. B and thickness of 102 mm. Chemical composition and mechanical properties of the exploited and new PM according to the certificate documentation are given in Tables 1 and 2.

Table 1. Chemical composition of exploited and new PM specimens.

Specimen designation	% mas.							
	C	Si	Mn	P	S	Cr	Mo	Cu
E	0.15	0.31	0.56	0.007	0.006	0.89	0.47	0.027
N	0.13	0.23	0.46	0.009	0.006	0.85	0.51	0.035

Table 2. Mechanical properties of exploited and new PM specimens.

Specimen designation	Yield stress, $R_{p0.2}$ (MPa)	Tensile strength, R_m (MPa)	Elongation, A (%)	Impact energy (J)
E	320	450	34.0	155
N	325	495	35.0	165

Welding of steel sheets of exploited and new PM is performed in two stages, according to the requirements given in the welding procedure, provided by a welding specialist, and these stages include:

- root weld by manual arc welding procedure (MMAW), using a coated LINCOLN S1 19G electrode (AWS: E8018-B2), and
- filling by submerged arc welding (SAW), wire denoted as LINCOLN LNS 150 and powder LINCOLN P230 used as consumables.

Chemical composition of coated electrode LINCOLN S1 19G, and wire LINCOLN LNS 150 according to certificate documentation is given in Table 3, with their mechanical properties given in Table 4.

Butt welded joint is made with a U-weld. The shape of the groove for welding preparation is chosen based on sheet thickness, in accordance with appropriate standards SRPS EN ISO 9692-1:2012, /2/, and SRPS EN ISO 9692-2:2008, /3/.

Table 3. Chemical composition of welding consumables.

consumable material	% mas.						
	C	Si	Mn	P	S	Cr	Mo
LINCOLN Sl 19G	0.07	0.31	0.62	0.009	0.010	1.17	0.54
LINCOLN LNS 150	0.10	0.14	0.71	0.010	0.010	1.12	0.48

Table 4. Mechanical properties of consumable material.

consumable material	Yield stress, $R_{p0.2}$ (MPa)	Tensile strength, R_m (MPa)	Elongation, A (%)	Impact energy (J) at 20°C
LINCOLN Sl 19G	515	610	20	> 60
LINCOLN LNS 150	495	605	21	> 80

IMPACT TESTS

Determining the amount of work required for fracture under defined test conditions is typically used for current control of quality and material homogeneity, as well as its treatment. This test procedure can be used to determine the tendency toward brittle fracture, i.e. the tendency toward an increase in brittleness during exploitation (ageing). The test procedure and the geometry of specimens, Fig. 1, is defined in accordance with SRPS EN 10045-1, /4/, i.e. ASTM E23-02 standard, /5/.

The notch position relative to the welded joint is defined according to EN 875 standard, /6/, Fig. 2. The notch is typically made by grinding, in a way that ensures that there is no change in the material during the process. No visible signs of machining should be present at the root of the notch.

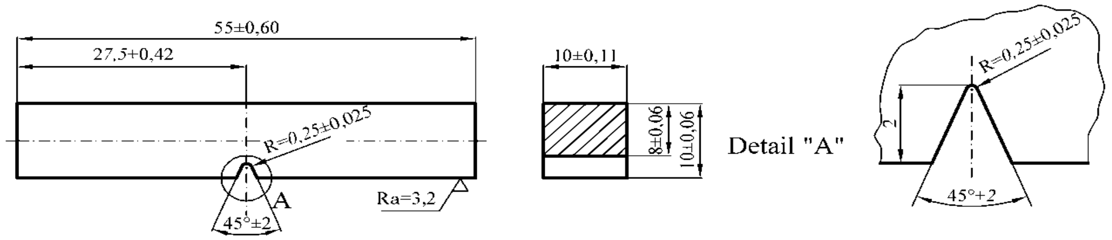

Figure 1. Geometry and dimensions of a standard V-notch specimen used for Charpy test method, /5/.

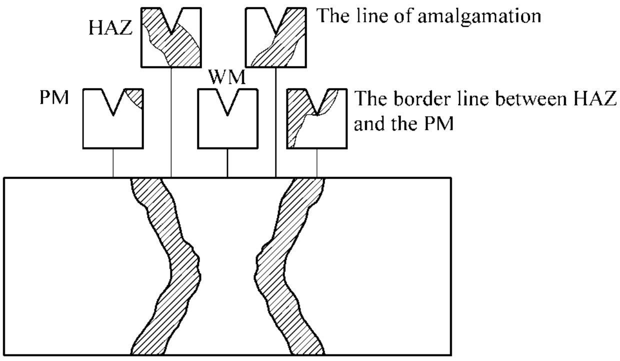

Figure 2. Notch position relative to the welded joint, /6/.

Impact tests of notched specimens with a butt welded joint in new and exploited PMs, WM and HAZ on new PM and exploited PM sides are performed at room temperature 20°C, and working temperature of 540°C.

Since the tests of new and exploited PMs, along with welded joint components, are performed using instrumented Charpy pendulum with an oscilloscope, wherein two types of diagrams are obtained (force-time and energy-time), it is possible to assess the influence of test temperature and exploitation period on the values of crack initiation energy, A_I, and crack propagation energy A_P, as components of the total impact energy, A_{tot}.

Test results for new and exploited PMs specimens tested at room temperature of 20°C and working temperature of 540°C are shown in Tables 5 and 6, /1/.

Typical force-time and energy-time diagrams obtained by testing at room temperature for the specimen designated as PM-1-1n, with a V-notch in the new PM, are shown in Fig. 3, whereas Fig. 4 shows diagrams for the specimen designated as PM-2-1n, for room temperature tests, /1/.

Force-time and energy-time diagrams for V-notched specimens from exploited PM, WM and HAZ, for both new PM and exploited PM and HAZ sides, are tested at room and working temperatures, but are not presented here due to the scope of this paper, /1/.

Table 5. Results of impact tests of notched specimens in the new PM.

Specimen designation	Testing temperature (°C)	Impact total energy A_T (J)	Crack initiation energy A_I (J)	Crack propagation energy A_P (J)
PM-1-1n	20	204	47	157
PM-1-2n		212	49	163
PM-1-3n		214	49	165
PM-2-1n	540	137	38	99
PM-2-2n		139	40	99
PM-2-3n		145	41	104

Table 6. Results of impact tests of notched specimens in the exploited PM.

Specimen designation	Testing temperature (°C)	Impact total energy A_T (J)	Crack initiation energy A_I (J)	Crack propagation energy A_P (J)
PM-1-1e	20	93	48	45
PM-1-2e		92	44	48
PM-1-3e		100	45	55
PM-2-1e	540	79	33	46
PM-2-2e		75	31	44
PM-2-3e		81	32	49

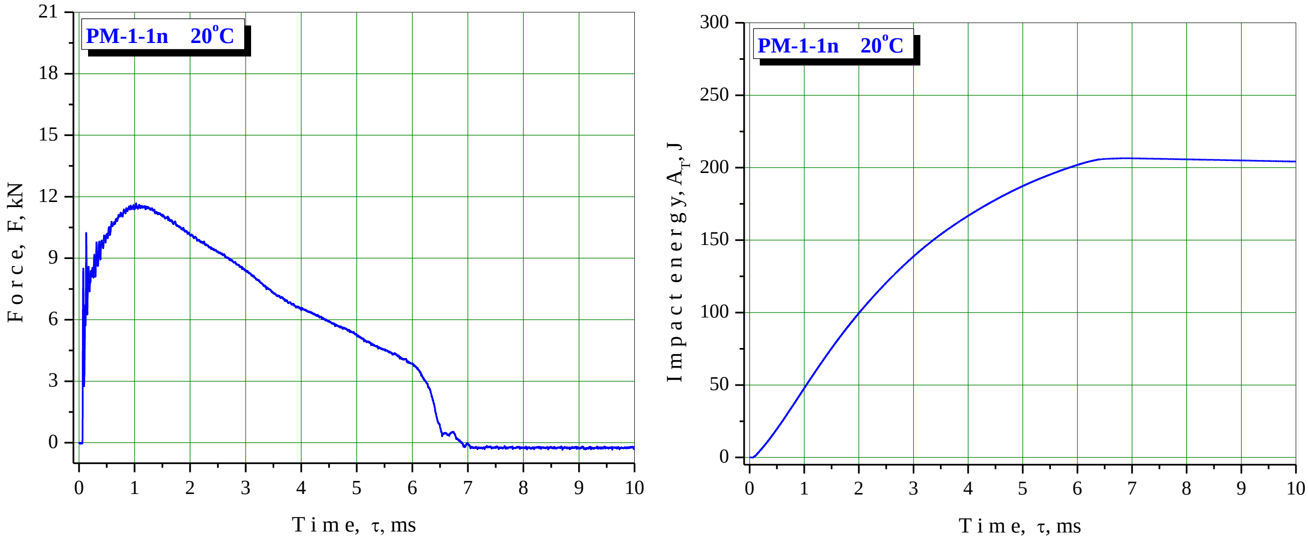

Figure 3. Diagrams from impact testing specimen PM-1-1n. Left (force-time), right (energy-time).

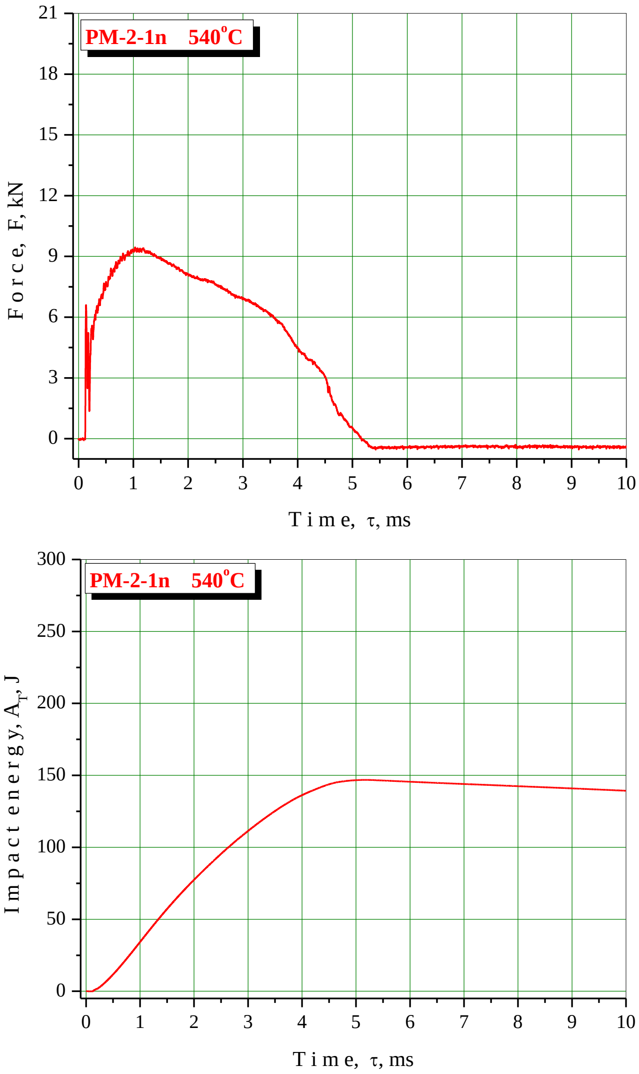

Figure 4. Diagrams for impact testing of specimen PM-2-1n: (upper) force-time, (lower) energy-time.

Dependence of total impact energy, A_{tot}, of the new and exploited PM, from test temperature is given in a diagram, Fig. 5. The influence of exploitation conditions on the values of crack initiation energy, A_I, and crack propagation energy, A_P, is given in a diagram, Fig. 6, for the new PM, and in Fig. 7, for exploited PM, /1/.

Test results for WM specimens tested at room, 20°C, and at working temperature 540°C are given in Table 7, /1/.

The influence of test temperature on the variation of total impact energy, A_{tot}, for notched WM specimens is presented in a diagram, Fig. 8. The change in the share of crack initiation and propagation energies in total impact energy, due to test temperature is given in Fig. 9, /1/.

Test results for HAZ specimens on new and exploited PM sides, tested at room- and working temperatures, are given in Tables 8 and 9, /1/. Dependence of total impact energy, A_{tot}, with temperature, obtained by testing V-notched HAZ specimens from new and exploited PM sides, is shown in a diagram, Fig. 10.

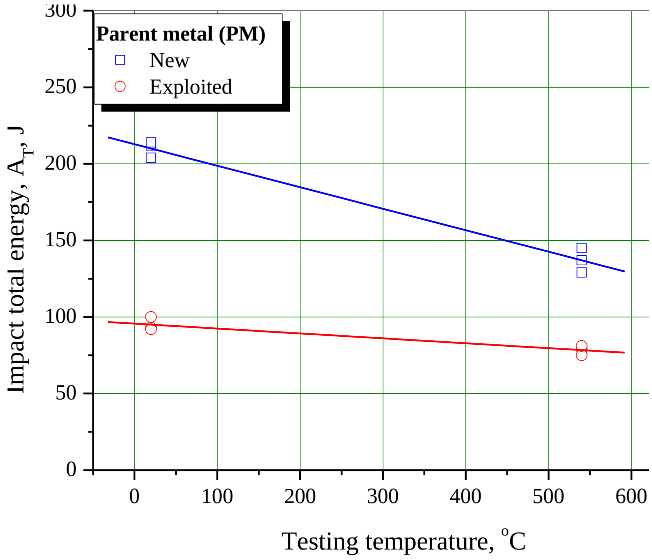

Figure 5. A_{tot} vs. temperature for new and exploited PM.

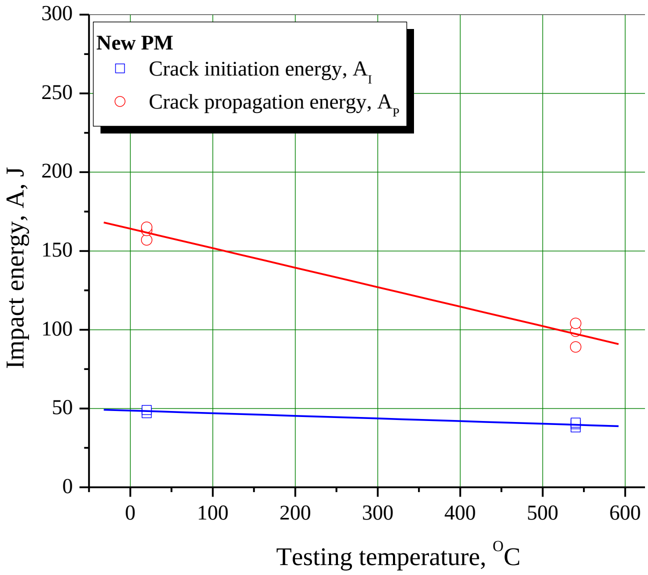

Figure 6. A_I and A_P vs. temperature for the new PM.

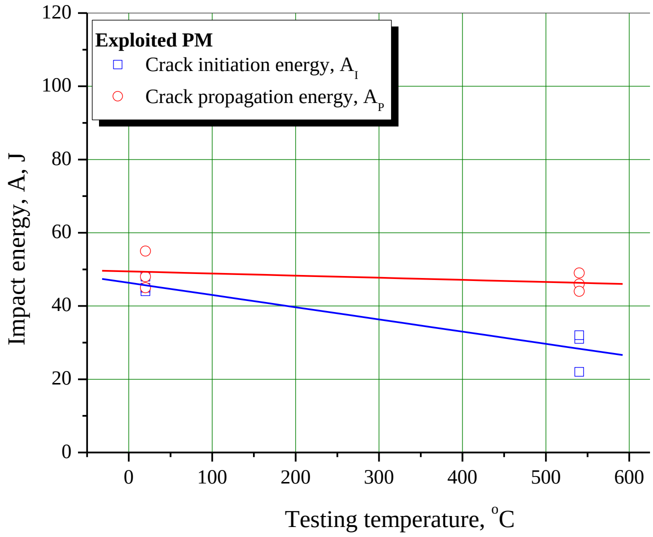

Figure 7. A_I and A_P vs. temperature for exploited PM.

Table 7. Results of impact test for notched WM specimens.

Specimen designation	Testing temperature (°C)	Impact total energy A_T (J)	Crack initiation energy A_I (J)	Crack propagation energy A_P (J)
WM-1-1	20	193	56	137
WM-1-2		190	60	130
WM-1-3		183	60	123
WM-2-1	540	139	40	99
WM-2-2		133	39	94
WM-2-3		134	39	95

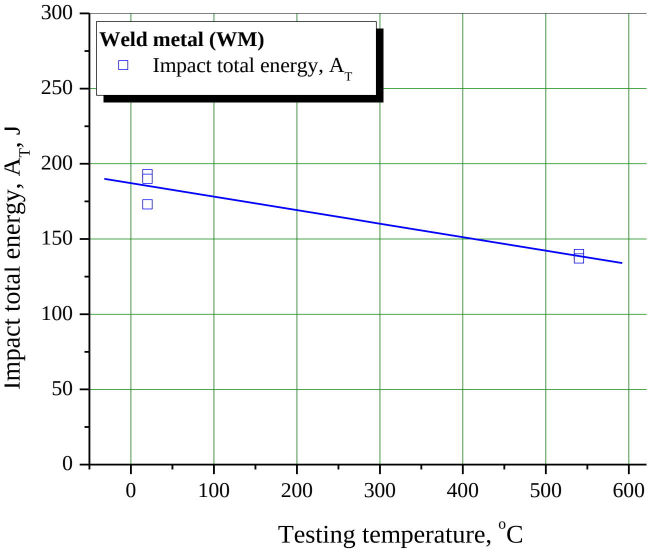

Figure 8. A_{tot} vs. temperature, for WM specimen tests.

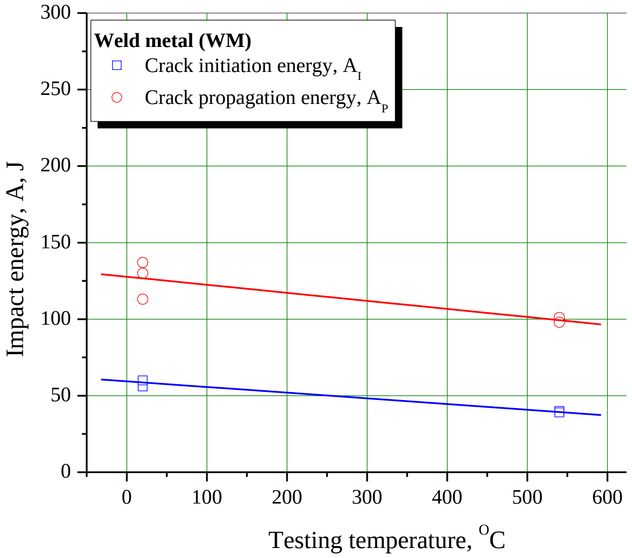

Figure 9. A_I and A_P vs. temperature for WM specimen.

Table 8. Results of impact tests of notched HAZ specimens.

Specimen designation	Testing temperature (°C)	Impact total energy A_T (J)	Crack initiation energy A_I (J)	Crack propagation energy A_P (J)
HAZ-1-1n	20	186	47	139
HAZ-1-2n		187	45	142
HAZ-1-3n		183	47	136
HAZ-2-1n	540	143	46	97
HAZ-2-2n		131	43	88
HAZ-2-3n		129	42	87

Table 9. Results of impact test of notched exploited HAZ specimens.

Specimen designation	Testing temperature (°C)	Impact total energy A_T (J)	Crack initiation energy A_I (J)	Crack propagation energy A_P (J)
HAZ-1-1e	20	96	44	52
HAZ-1-2e		88	42	46
HAZ-1-3e		80	43	37
HAZ-2-1e	540	76	31	45
HAZ-2-2e		75	30	45
HAZ-2-3e		76	30	46

The influence of exploitation period and temperature on crack initiation and propagation energies, as parts of the total impact energy in V-notched HAZ specimens for the new PM is shown in Fig. 11, and for specimens from the exploited PM side, this influence is shown in Fig. 12, /1/.

Based on results from impact testing new and exploited PM, it can be seen that an increase in exploitation period and test temperature leads to a decrease in total impact energy, A_{tot}, Fig. 5. Total impact energy, in the case of new PM, ranges from 210 J (20°C) to 141 J (540 °C). Exploitation period additionally reduces total energy, thus in case of exploited PM, A_{tot} ranges from 95 J at room temperature, down to 78 J at working temperatures, /1/.

The share of crack initiation energy, A_I, in new PM notched specimens, ranges from 48 J at room temperature to 40 J at working temperature. Crack propagation energy, A_P, changes from 162 J at room temperature to 101 J at working temperature, Fig. 6. The share of crack initiation energy for exploited PM is similar to values obtained for new PM at 20°C and has an average of 46 J, whereas for 540°C it decreases to 32 J. Exploitation period and test temperature significantly influence the crack propagation energy, ranging from 49 J at 20°C to 46 J at 540°C, /1/.

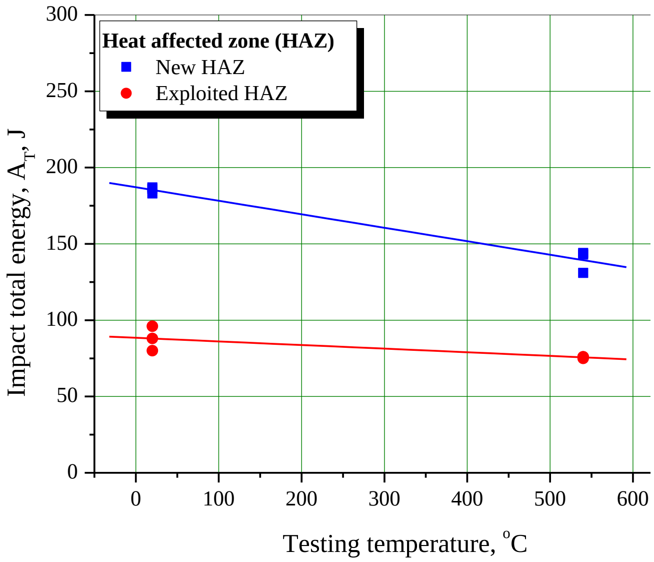

Figure 10. A_{tot} vs. temperature for the HAZ.

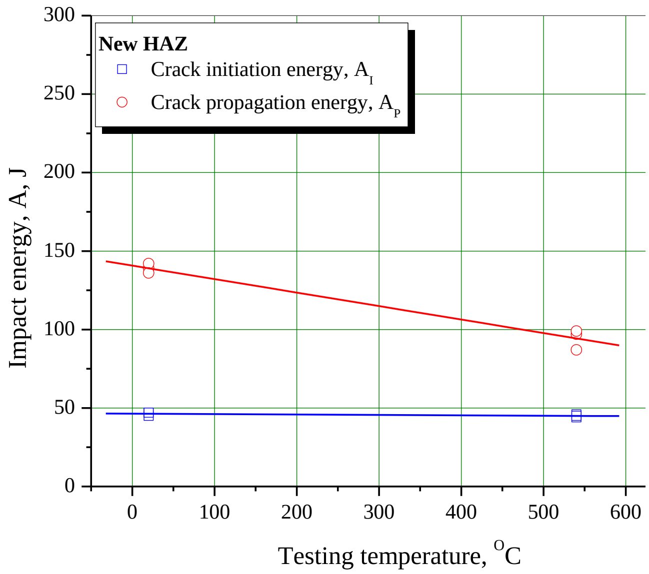

Figure 11. A_I and A_P vs. temp. for HAZ specs. (new PM side).

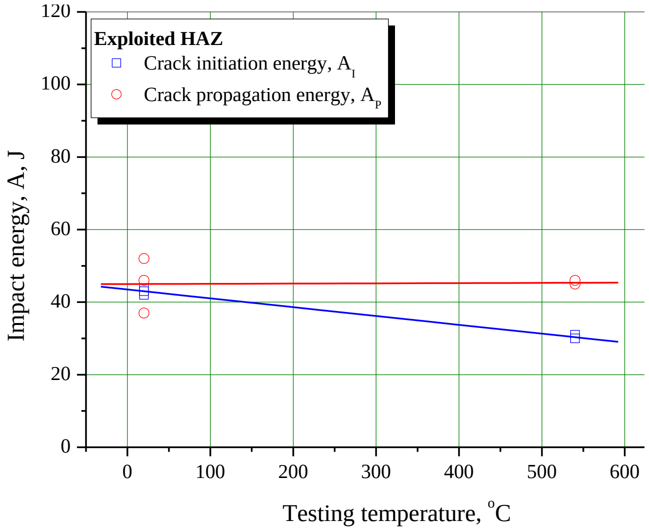

Figure 12. A_I and A_P vs. temperature for HAZ specimens (exploited PM side).

DISCUSSION

The values of total impact energy, A_{tot}, for notched WM specimens range from 189 J obtained at 20°C down to an average value of 135 J at 540°C, Fig. 8. The share of crack initiation energy, A_I, ranges from an average of 59 J at 20°C to 39 J obtained at 540°C. The value of crack propagation energy, A_P, also decrease with an increase in temperature, from 130 J at 20°C to 96 J at 540°C, Fig. 9, /1/.

Lowest impact properties are obtained for notched HAZ specimens. However, compared to the values obtained for the PM, they are negligibly lower, which can be attributed to a well performed thermal treatment. Total impact energy, A_{tot}, for notched HAZ specimens on the new PM side decreases from 185 J at 20°C to 134 J at 540°C, Fig. 10. It can be noticed that the test temperature does not have a significant effect on crack initiation energy. Namely, the crack initiation energy is around 45 J in both cases. Crack propagation energy ranges from 139 J at 20°C to 90 J at 540°C, Fig. 11, /1/.

The influence of test temperature in the case of exploited HAZ specimens indicates a slightly different behaviour compared to the results obtained from tests of new HAZ specimens. The total impact energy for HAZ specimen on the exploited PM side ranges from 88 J obtained at 20°C down to 76 J obtained at 540°C, Fig. 10. In the case of exploited HAZ specimens, the exploitation period affects the crack initiation energy. The share of crack initiation energy, for HAZ specimens from exploited PM side averages to 43 J at 20°C and decreases to 30 J for specimens tested at 540°C. However, the test temperature does not affect the crack propagation energy, which is around 45 J at both 20°C and 540°C, Fig. 12, /1/.

CONCLUSIONS

Based on results of impact tests, i.e. the determined total impact energy, A_{tot}, it is clear that the total energy depends on:
- the location of the V-notch, i.e. whether it is within the PM, WM or the HAZ;
- test temperature, and
- the exploitation period, i.e. if the notch is located in the new or exploited PM, or in the HAZ on new or exploited PM side.

The highest total impact energy is observed in notched WM specimens, whereas these values for WM and HAZ notched specimens are slightly lower. Tests have indicated a nearly identical influence of test temperature on the total impact energy. Total impact energy decreases with an increase in temperature, and the influence of the temperature is most noticeable in V-notched PM and HAZ specimens.

The exploitation period has a significant effect on the variation of total impact energy. Whether the notch is located in the new or exploited PM, or in the HAZ on the new or exploited PM sides, is of great importance. Exploitation period significantly reduces total impact energy in the case of specimens with the notch in the exploited PM, and for notched HAZ specimens (exploited PM side). This phenomenon can be related to structural changes in the material due to exploitation period (as in the case of tensile tests).

Testing of V-notched PM specimens has shown that the ratio of crack initiation energy to crack propagation energy changes, depending on test temperature and exploitation period. With increase in temperature, the ductile component share in total impact energy (crack propagation energy) decreases, whereas the brittle component fraction (crack initiation energy) increases. The character of force-time and energy-time curves obtained by testing specimens at room temperature corresponds to ductile material behaviour, with a small share of crack initiation energy and a significant share of crack propagation energy, whereas the character of the same curves for tests performed at working temperature are somewhat less favourable in terms of total impact energy components ratio, i.e. it has a nearly equal share of crack initiation and crack propagation energy.

In the case of testing V-notched WM specimens, the increase in temperature also decreases the share of the ductile component of total impact energy, whereas the brittle component share increases.

Specimens with the notch in HAZ have shown the highest influence of test temperature and exploitation period on the change in the ratio of crack initiation- and crack propagation energy. In case of notched HAZ specimens on the new PM side, the share in ductile component of the total impact energy (crack propagation energy) was three times larger (3:1), compared to the brittle component, and it decreased with an increase in temperature to a ratio of 2:1. For specimens with the notch in the exploited HAZ, this ratio is particularly unfavourable, and at room temperature the ratio of crack initiation to crack propagation energy is almost the same (1:1), whereas at working temperature of 540°C, it slightly changes to an approximate value of 1.5:1.

In general, the character of force-time and energy-time obtained by testing specimens with the V-notch located in the components of a new welded joint (new PM, WM and HAZ) at room and working temperature corresponds to the behaviour of ductile materials, with a small share of crack initiation energy, A_I, and a large share of crack propagation energy, A_P. In the case of exploited material tests at room and working temperature, the character of the curves corresponds to ductile-brittle material behaviour, with a similar share of crack initiation- and crack propagation energy. This information is of great significance for the selection of materials for real exploitation conditions.

Test results and their analyses have shown that the selected welding technology used for the replacement of a part of a reactor mantle is justified.

ACKNOWLEDGEMENTS

Parts of this research are supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through Mathematical Institute SANU Belgrade, Grant OI 174001 Dynamics of hybrid systems with complex structures.

REFERENCE

1. Čamagić, I., Investigation of the Effects of Exploitation Conditions on the Structural Life and Integrity Assessment of Pressure Vessels for High Temperatures (in Serbian), doctoral thesis, University of Pristina, Faculty of Technical Sciences, Kosovska Mitrovica, 2013.
2. SRPS EN ISO 9692-1:2012, Welding and allied processes - Recommendations for joint preparation - Part 1: Manual metal-arc welding, gas-shielded metal-arc welding, gas welding, TIG welding and beam welding of steels (ISO 9692-1:2003), 2012.
3. SRPS EN ISO 9692-2: 2008, Welding and allied processes - Joint preparation - Part 2: Submerged arc welding of steels (ISO 9692-2:1998), 2008.
4. SRPS EN 10045-1, Mehanička ispitivanja metala, Ispitivanje udarom po Šarpiju, Deo 1, Termini i definicije, 1993.
5. ASTM E 23-02, Standard Method for Notched Bar Impact Testing of Metallic Materials, Annual Book of ASTM Standards, Vol. 03.01, 2002.
6. EN 875, Welded butt joints in metallic materials - Specimen, location and notch orientation for impact test, 1995.
7. Kudrin, V., Steelmaking, Mir Publishers, 1989, p.11-12.