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THE INFLUENCE OF BUFFER LAYER ON THE PROPERTIES OF SURFACE WELDED JOINT OF HIGH-CARBON STEEL

VPLIV VMESNE PLASTI NA LASTNOSTI POVRŠINSKIH ZVAROV JEKLA Z VELIKO OGLJIKA

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Surface welding with buffer layer is often in use because of its well-known properties of plasticity, or ability to slow crack growth initiated. However, in modern surface welding technologies, buffer layer is rarely used. New classes of flux-cored and self-shielded wires are recently developed and it is possible to achieve the requested properties of welded joints without buffer layer. In this paper, for comparison, the high-carbon steel surface was welded with and without buffer layer. In both cases, it has been used same surface process, but with different filler materials and equal heat input. The mechanical properties, total impact energy, as its components, the fatigue threshold value of ΔK_{th}, and the crack growth rate da/dN were determined. The results obtained at room temperature show better properties of the sample surface welded with the buffer layer, but, with temperature decrease a sharp decrease of toughness of the sample welded with buffer layer occured. Also, buffer layer didn't change the property of initiated crack in terms of crack growth rate. The construction from high-carbon steel are exposed to low exploitation temperature and are used for prolong working time, thus the use of buffer layer in modern surface welding technologies is not recommended.

Keywords: surface welding, buffer layer, welded joint, toughness, crack growth parameters

Površinsko varjenje z vmesno (buffer) plastjo se večkrat uporablja zaradi dobre plastičnosti in sposobnosti za preprečevanje rasti nastale razpoke. Vendar se redkeje uporablja pri sodobnih tehnologijah površinskega varjenja. Nove vrste polnjene in samozaščitne žice so bile razvite in je bilo tako mogoče doseči zahtevane lastnosti zvarov brez vmesne plasti. V tem delu je opisana zavarjena površina jekla z veliko ogljika z vmesno plastjo in brez nje. V obeh primerih je bil uporabljen enak proces z enakim vnosom toplote, vendar z različnim varilnim materialom. Določene so bile mehanske lastnosti, skupna žilavost in njene komponente, prag utrujenosti ΔK_{th} in hitrost napredovanja razpoke da/dN. Lastnosti pri sobni temperaturi so boljše pri vzorcu površine, ki je bil zavarjen z vmesno plastjo, vendar se je pri znižanju temperature hitro zmanjšala žilavost vzorca, ki je bil zvarjen z vmesno plastjo. Tudi vmesna plast ni spremenila hitrosti rasti začete razpoke. Konstrukcije iz jekla z veliko ogljika obratujejo pri nizki temperaturi in se uporabljajo dolgo časa. Zato ni priporočena uporaba vmesne plasti pri modernih tehnologijah varjenja površine.

Ključne besede: varjenje površine, vmesna plast, zvar, žilavost, parametri rasti razpoke

1 INTRODUCTION

The main properties of high-carbon steels are high hardness and strength and having a pearlitic microstructure, have a typically low toughness and crack growth resistance also. Since in exploitation they are often exposed to wear and rolling contact fatigue, parts become unfit for service due to unacceptable profiles, cracking, spalling etc. Surface welding is maintenance way to prolong the exploitation life of damaged parts.[1] For surface welding are mostly in use semi-automatic arc welding processes, with flux-cored and self-shielded wires. Basic difference between them is that the first requires an external shielding gas. In both cases, core material acts as a deoxidizer, helping to purify the weld metal, generate slag formers and by adding alloying elements to the core, it is possible to increase the strength and provide other desirable weld metal properties.[2,3] These processes have replaced slowly MMA process and they almost ideal for outdoors in heavy winds. The result of flux-cored wire application are higher quality welds, faster welding and maximizing a certain area of welding performance.[4] The number of layers in surface welded joint depends of the damage degree, most frequently it's consists of three layers, sometimes with buffer layer, also. The buffer layer is applied for the crack sensitive materials, what high carbon steel certainly is (high CE). The function of buffer layer is to slow down the growth of initiated crack with its own plasticity. Constructions, like railways, are exposed to cyclic load and wear in exploatation, that the crack initiate. Sometimes it is necessary to use a buffer layer, which besides good affects, may have drawbacks, also. Namely, the use of buffer layer slows down significantly the surface welding process, due to replacement of wires and settings of other welding parameters. Since, as already noted, for surface welding are used mainly semi-automatic and automatic processes, it significantly extends the working time. New classes of flux-cored and self-shielded wires are developed recently, and it is possible to achieve the requested properties of welded joints without buffer layer.

2 EXPERIMENTAL PROCEDURE

The investigation was carried out with high carbon steel with 0.52C-0.39Si-1.06Mn-0.042P-0.038S-0.011Cu-0.006Al, having initial pearlitic microstructure and tensile strength of 680–830 N/ mm^2.

The surface welding of the testing plates was perfomed with a semi-automatic process. As the filler material, the self-shielded wire (FCAW-S) and flux-cored wires (FCAW) with chemical compositions and mechanical properties given in **Table 1**, were used. The plates were surface welded in three layers; sample 1 with FCAW-S without buffer layer; sample 2 with FCAW with buffer layer, as shown in **Table 1**.

Since the *CE*-equivalent was *CE* = 0.64[4], the heat input during welding was of 10 kJ/cm, the preheating temperature was of 230 °C, and the controlled interpass temperature was of 250 °C. Sample 1 was surfaced with one type of filler material (self-shielded wire), while for surfacing of sample 2 two types of wires were used, but both flux-cored: one for the buffer layer and the second for the last two layers. As shielded gas for welding of sample 2, CO_2 was used. To evaluate the mechanical properties, specimens for further investigation were cut from surface welded joints.

3 HARDNESS

Hardness measurements were performed using the 100 Pa load. The hardness profiles of surface welded joints are shown in **Figure 1**. The lowest hardness is for the base metal (250–300 HV), being the hardness of naturally cooled standard rails.[5,6] In HAZ hardness increase is noticable in both samples, due to complex heat treatment and grain refinement.[4] In sample 2 in the first surfaced layer, i.e. in buffer layer the hardness is decreased sharply. The function of buffer layer is to stop the growth crack initiates with own plasticity and lower hardness. The hardness of II and III welded layers of both samples are the highest and similar, due to influence of alloying elements in filler materials, which shift transformation points to bainitic region.[4] The maximum hardness level of 350–390 HV is reached in surface welded layers and it provides improvement of mechanical properties and wear resistance.[4]

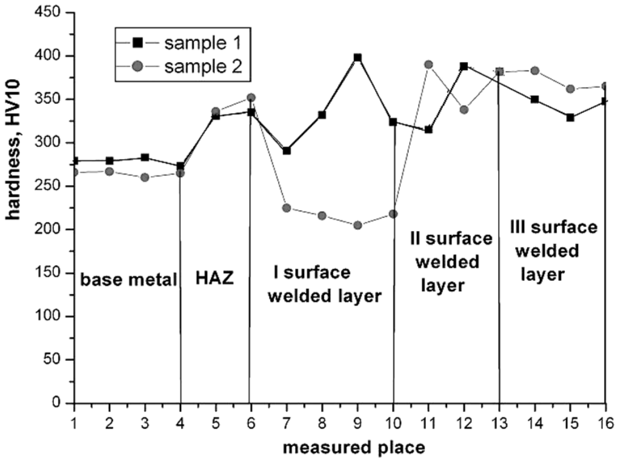

Figure 1: Hardness profiles along the joint cross-section of samples
Slika 1: Profili trdote na prečnem prerezu vzorcev

4 TENSILE TESTS

The tensile tests were performed on a 2 mm thick specimens. The room temperature mechanical properties (ultimate tensile strength, UTS) of the surface welding layers are shown in **Figure 2**. The basic requirement in

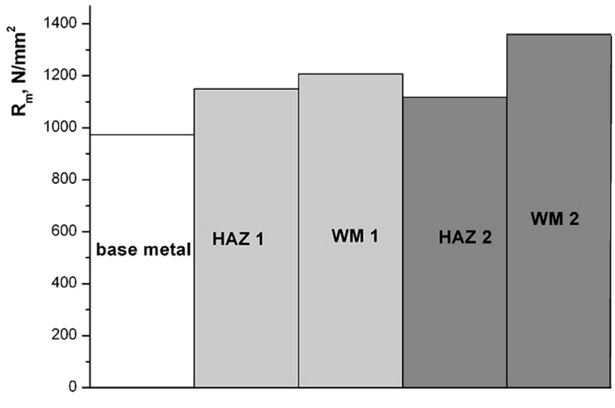

Figure 2: Ultimate tensile strength of the surface welded joints
Slika 2: Raztržna trdnost površinskih zvarov

Table 1: Chemical composition of filler materials
Tabela 1: Kemična sestava varilnih materialov

Sample No.	Wire designation		Wire diam. *d*/mm	Chemical composition, mass fractions, *w*/%							Hardness, HRC
				C	Si	Mn	Cr	Mo	Ni	Al	
Sample 1	OK Tubrodur 15.43 (self-shielded wire)		1.6	0.15	<0.5	1.1	1.0	0.5	2.3	1.6	30–40
Sample 2	1.layer (buffer layer)	Filtub 12B (flux-cored wire)	1.2	0.05	0.35	1.4	-	-	-	-	-
	2. and 3. layer	Filtub dur 12 (flux-cored wire)	1.6	0.12	0.6	1.5	5.5	1.0	-	-	37–42

welded structures design is to assure the required strength. In most welded structures this is obtained with superior strength of WM compared to BM (overmatching effect), and in tested case this is achieved[7,8]. The highest UTS was found for the weld metal of sample 2 (1210 MPa), due to solid state strengthening by alloying elements.[9]

5 IMPACT TESTING

The impact testing was performed according to EN 10045-1, i.e ASTM E23-95, with Charpy V notched specimens on the instrumented machine SCHENCK TREBEL 150 J. Impact testing results are given in **Table 2, 3** and in **Figure 3** for base metal and HAZ at all testing temperatures. The total impact energy, as well as crack initiation and crack propagation energies, for weld metal of both samples at all testing temperatures are presented in **Table 4** and in F**igure 4**.

The total energy of base metal is very low (5 J), due to very hard and very brittle cementite lamellae in pearlite microstructure,[4] while the toughness of HAZ is higher (11–12 J) and is similar for both samples at all testing temperatures.

Table 2: Instrumented impact testing results of Charpy V specimens for base metal and HAZ at all testing temperatures
Tabela 2: Rezultati instrumentiranih Charpyjevih preizkusov za osnovni material in HAZ pri vseh temperaturah preizkušanja

	Total impact energy, E_u/ J		
	20 °C	–20 °C	–40 °C
base metal	5	3	3
sample 1-HAZ 1	12	11	10
sample 2-HAZ 2	11	10	9

Table 3: Instrumented impact testing results of Charpy V surface weld metal specimens at all testing temperatures
Tabela 3: Rezultati instrumentiranih Charpyjevih preizkusov za vzorce V površinskih zvarov pri vseh temperaturah preizkušanja

	sample 1-WM1			sample 2-WM2		
	20 °C	–20 °C	–40 °C	20 °C	–20 °C	–40 °C
Total impact energy, E_u/ J	29	23	17	34	14	11
Crack initiation energy, E_{in}/ J	20	16	15	12	10	10
Crack propagation energy, E_{pr}/ J	9	7	2	22	4	1

The total impact energy of samples 1 and 2 at room temperature are significantly higher (29 J and 34 J) than in base metal (5 J), as consequence of appropriate choice of alloying elements in the filler material. The presence of Ni, Mn and Mo promotes the formation of needled bainitic microstructure and grain refinements, and increases the strength and toughness also[9]. By analyzing the impact energy values of sample 1, a change of toughness in continuity is observed, with no marked drop of toughness, and for all tested temperatures, crack initiation energy is higher than crack propagation energy. This

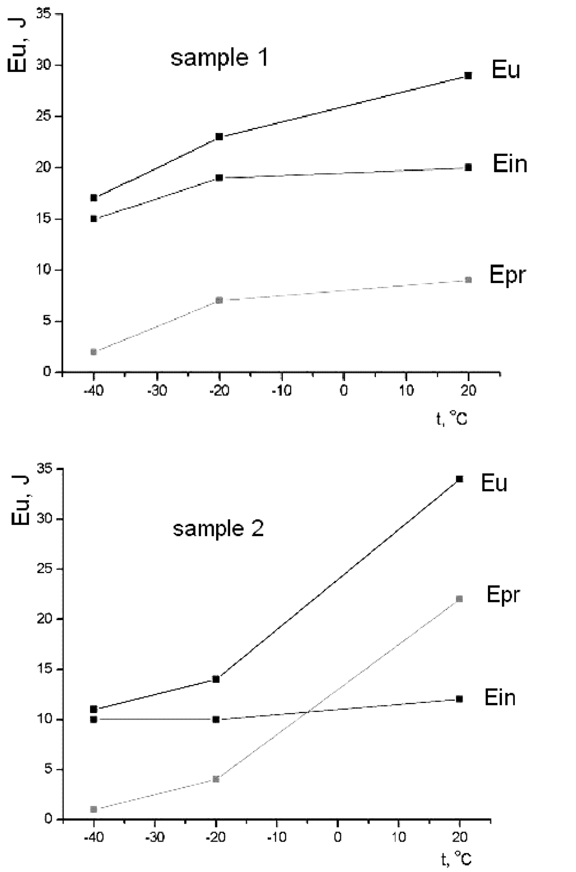

Figure 3: Dependence total impact energy, crack initiation and crack propagation energy vs.temperature for a) weld metal of sample 1 and b)weld metal of sample 2
Slika 3: Odvisnost skupne žilavosti ter energije začetka in napredovanja razpoke od temperature za zvar vzorca 1 in zvar vzorca 2

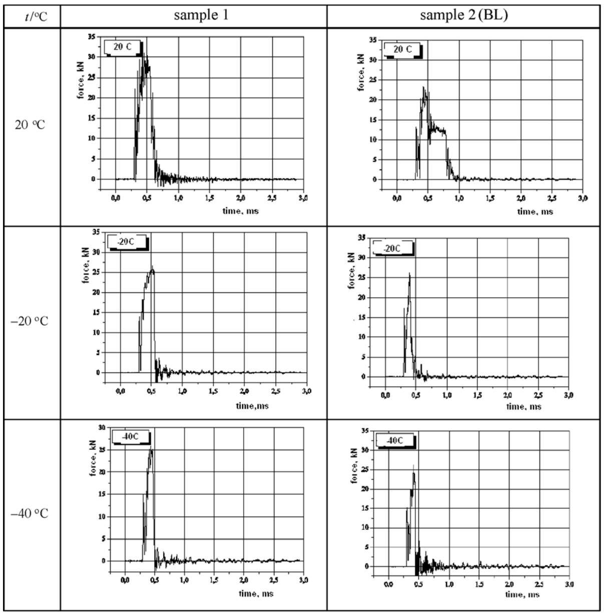

Figure 4: Diagrams force-time, obtained by instrumented Charpy pendulum for sample 1 and sample 2
Slika 4: Odvisnost sile od časa, določena z instrumentalnim Charpyjevim kladivom za vzorca 1 in 2

is the reason for the absence of significant decrease of toughness. The highest value of total impact energy was found for the sample 2 at room temperaure (34 J), which is the only case when the initiation energy is lower than propagation energy (12 J and 22 J, respectivelly). This shown practically the buffer layer function. Namely, the initiated crack during propagation comes to plastic buffer layer, which slows down crack further growth. For this reason, the crack propagation energy is the largest part of total impact energy. However, at –20 °C, significant drop of total impact energy is noticable (14 J) due to losing of buffer layer plastic properties at lower temperatures. The low-carbon wire (0.05 % C and 1.4 % Mn) has excellent toughness, but and marked rapid drop on S-curve (dependence toughness vs. temperature). Transition temperature of this material above –20 °C is confirmed by the obtained impact toughness results. The use of buffer layer is reasonable if the exploatation temperature is above –5 °C; on the contrary, at lower temperatures, buffer layer is losing its function and the toughess is decreased.

Diagrams force-time, obtained by instrumented Charpy pendulum, are given in **Figure 5**. As can be seen, for the sample 1 the character of diagrams force-time changed little by lower temperature. Namely, this material at room temperature has diagram with marked rapid drop, as consequence of unstable crack growth. After the maximum load, a very fast crack growth is started, and it is confirmed by the low value of crack propagation energy.[10] On the contrary, on the sample 2 diagram at room temperature, the presence of buffer layer is clearly shown. The initiated crack, during its growth, comes to buffer layer which temporary stops the further crack growth and changes crack growth rate. The obtained experimental diagram doesn't belong to any type, according to standard EN 10045-1. This leads to toughness increase, primarily crack propagation energy, and it is also here the only case when the crack initiation energy is lower than crack propagation energy.

6 CRACK GROWTH RATE

A basic contribution of fracture mechanics in fatigue analysis is the division of fracture process to crack initiation period and the growth period to critical size for fast fracture[7]. Fatigue crack growth tests had been performed on the CRACKTRONIC dynamic testing device in FRACTOMAT system, with standard Charpy size specimens, at room temperature, and the ratio $R = 0.1$. A standard 2 mm V notch was located in third layer of WM, for the estimation of parameters for WM and HAZ, since initiated crack will propagate through those zones. Crack was initiated from surface (WM) and propagated into HAZ, enabling calculation of crack growth rate d*a*/d*N* and fatigue treshold ΔK_{th}.[4] The results of crack growth resistance parameters, i.e., obtained relationship d*a*/d*N* vs. ΔK for sample 1 and for sample 2 are given in **Figure 6**. Parameters C and m in Paris law, fatigue threshold ΔK_{th} and crack growth rate values are given in **Table 5** for both samples as obtained from relationships given in **Figure 6**, for corresponding ΔK values.

The behaviour of welded joint and its constituents should affect the change of curve slope in the part of validity of the Paris law. Materials of lower fatigue-crack growth rate have lower slope in the diagram d*a*/d*N* *vs.* ΔK.[7] For comparison of the properties of surface welded joint constituents the crack growth rates are calculated for different values of stress-intensity factor range ΔK. Bearing in mind that the weld metal consists of two lay-

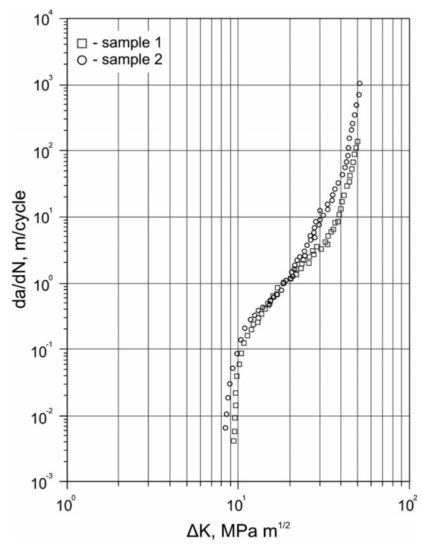

Figure 6: Diagram d*a*/d*N* vs. ΔK for sample 1 and sample 2
Slika 6: Diagram d*a*/d*N* za vzorca 1 in 2

Table 4: Parameters C, m, ΔK_{th} and crack growth rate values for all zones of surface welded joints
Tabela 4: Parametri C, m, ΔK_{th} in hitrost rasti razpoke za vse dele površinsko zvarjenih vzorcev

	Zone of surface welded joint	Fatigue threshold ΔK_{th}/(MPa m$^{1/2}$)	Parameter C	Parameter m	Crack growth rate (d*a*/d*N*)/m		
					$\Delta K = 15$ MPa m$^{1/2}$	$\Delta K = 20$ MPa m$^{1/2}$	$\Delta K = 30$ MPa m$^{1/2}$
sample 1	WM 1	9,5	$4.45 \cdot 10^{-13}$	3.74	$1.11 \cdot 10^{-8}$	-	-
	WM 2		$3.78 \cdot 10^{-13}$	3.61	-	$1.88 \cdot 10^{-8}$	-
	HAZ		$4.07 \cdot 10^{-13}$	3.79	-	-	$1,61 \cdot 10^{-7}$
sample 2	WM 1	8,9	$4.63 \cdot 10^{-13}$	3.87	$1.65 \cdot 10^{-8}$	-	-
	WM 2		$3.85 \cdot 10^{-13}$	3.88	-	$2.07 \cdot 10^{-7}$	-
	HAZ		$3.76 \cdot 10^{-13}$	3.93	-	-	$1.18 \cdot 10^{-6}$

ers (third layer is used for V notch), as referent values of ΔK were taken: ΔK = 15 MPa $m^{1/2}$ for WM1, ΔK = 20 MPa $m^{1/2}$ for WM2, and ΔK = 30 MPa $m^{1/2}$ for HAZ. It's important that all the selected values are within the middle part of the diagram, where Paris law is applied. In all three zones of surface welded joint (WM2, WM1 and HAZ), the sample 2 with buffer layer has a higher crack growth rate than sample 1, i.e. the growth of initiated crack will be slower in sample 1. This means that for the same value of stress intensity factor ΔK, the specimen of sample 2 needs less number of cycles of variable amplitude than the specimen of sample 1, for the same crack increment.[9] The maximum fatigue crack growth rate is achieved in HAZ for both samples, when stress intensity factor range approaches to plane strain fracture toughness.

If a structural component is continuously exposed to variable loads, fatigue crack may initiate and propagate from severe stress raisers if the stress intensity factor range at fatigue threshold ΔK_{th} is exceeded.[7] The fatigue treshold value $\Delta K_{\rm th}$ for sample 2 ($\Delta K_{\rm th}$ = 8.9 MPa $m^{1/2}$) is lower than that for sample 1 ($\Delta K_{\rm th}$ = 9.5 MPa $m^{1/2}$). This means that the crack in sample 2 will be initiated earlier, i.e. after less number of cycles, than in sample 1.

Values of fatigue threshold and crack growth rates corespond to initiation and propagation energies in impact testing, and in this case, good corelation is achieved.[9] Sample 1 has higher crack initiation energy (20 J) and higher $\Delta K_{\rm th}$ ($\Delta K_{\rm th}$ = 9.5 MPa $m^{1/2}$ for sample 1 and $\Delta K_{\rm th}$ = 8.9 MPa $m^{1/2}$ for sample 2). With comparation of crack propagation energy and crack growth rate, it is hard to establish the precise analogy, as toughness was estimated for the surface weld metal, whereas crack growth rate for each surface welded layer. Generally, buffer layer didn't show slow,, the initiated crack growth, with aspect of crack growth rate, while this effect is obvious in the case of toughness, i.e. crack propagation energy.

7 CONCLUSIONS

On the base of obtained experimental results and their analysis, the following is concluded:

1. The experimental investigation of surface welded joints with different weld procedures has shown, as expected, significant differences on their performance in terms of mechanical properties. But, in both cases, it was shown, that in spite of poor weldability of high carbon steel, they can be successfully welded.
2. The maximal hardness level of 350–390 HV is reached in surface welded layers of both samples, with equal hardness of base metal (250–300 HV). The main difference appears in the first deposition layer, where as expected, in sample 2 the hardness is significantly lower (buffer layer). The obtained hardness values ensure simultaneously the improvement of mechanical and wear properties, and in the case of a rail, represents maximal hardness preventing the wheel wear.[4] Similar results are obtained by tensile testing. Sample 2 has slightly higher ultimate tensile strength (1360 MPa) than sample 1 (1210 MPa) due to solid solution strengthening by alloying elements.
3. The greatest differences are found in impact properties. The highest value of total impact energy of sample 2 at room temperaure (34 J) was obtained only in the case when the initiation energy was lower than propagation energy (12 J and 22 J, respectivelly). However, at –20 °C, the drop of total impact energy is significant (14 J), due to lowering of buffer layer plastic properties at lower temperatures. The transition temperature of this material is above –20 °C, and it was confirmed by obtained impact toughness results. The use of buffer layer is beneficial for exploatation temperature above –5 °C. On the contrary, at lower temperatures, buffer layer loses its function and toughess decreases. On the contrary, for sample 1 the change of toughness is continous and without marked drop of toughness (29 J at 20 °C and 23 J at –20 °C). At all tested temperatures, the crack initiation energy is higher than crack propagation energy. This may be the reason for the absence of significant decrease of toughness and that should be kept in mind during design and exploitation.
4. Results show that sample 2 has higher crack growth rate ($1.65 \cdot 10^{-8}$) than sample 1 ($1.11 \cdot 10^{-8}$), and lower fatigue treshold value $\Delta K_{\rm th}$ (8.9 MPa $m^{1/2}$ for sample 2 and 9.5 MPa $m^{1/2}$ for sample 1). This means that the crack in sample 2 will be initiated earlier, i.e. after less number of cycles, than in sample 1, and that a less number of cycles is needed to reach the critical size.
5. Values of fatigue threshold and crack growth rates corespond to initiation and propagation energies in impact testing. In the case of fatigue treshold and crack initiation energy, good correlation was achieved. Sample 1 has higher crack initiation energy (20 J) and higher $\Delta K_{\rm th}$ (9.5 MPa $m^{1/2}$) than sample 2 (12 J and $\Delta K_{\rm th}$ = 8.9 MPa $m^{1/2}$). On the contrary, buffer layer didn't show decrease of initiated crack growth rate, as this effect is obvious in the case of toughness, i.e. crack propagation energy. Since the constructions from high-carbon steel are used at low temperature, and bearing in mind the extended working time, in modern surface welding technologies, the use of buffer layer is not recommended.

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