

INFLUENCE OF NON-METALLIC INCLUSIONS ON THE FORMATION OF HOT CRACKS IN THE WELD AND HEAT-AFFECTED ZONE

VPLIV NEKOVINSKIH VKLJUČKOV NA NASTANEK VROČIH RAZPOK V ZVARU IN TOPLOTNO VPLIVANI CONI

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A thick-walled casting of unalloyed cast steel with a high content of non-metallic inclusions was built up with the submerged arc-welding (SAW) process. Hot cracks were detected in the built-up, tough inner layer of unalloyed steel (near the fusion line alongside the edge of the prepared groove). The cause for it was an inappropriate "bead-to-bead" technique of building up, with a strong remelting of the base material and a strong contamination of the weld pool with non-metallic inclusions. The chemical composition of the inclusions also indicated an insufficient attention or technical difficulties during building, since some inclusions were based on the welding slag. The smallest possible content of the base-material admixture must be ensured, the welding slag fully removed and, if needed, before welding the next bead, the narrow and deep interpass groove must be widened and rounded off by grinding.

Keywords: surfacing, non-metallic inclusions, strong remelting of the base metal, hot cracking

Pri debelostenskem ulitku iz nelegirane jeklene litine z veliko vsebnostjo nekovinskih vključkov, navarjenem po postopku varjenja pod praškom (EPP), so bile v navarjeni žilavi vmesni plasti iz nelegiranega jekla v prvem sloju oziroma blizu linije spajanja ob robu pripravljenega utora ugotovljene vroče razpoke. Vzrok je bila neprimerna tehnika navarjanja "varek do varka", kar je imelo za posledico močno pretaljevanje osnovnega materiala in zato močno onesnaženje zvarne kopeli z nekovinskimi vključki. Kemijska sestava vključkov kaže tudi na nepazljivost ali na tehnološke težave med navarjanjem, saj so nekateri vključki na osnovi varilske žilindre. Nujno je zagotoviti čim manjše primešanje osnovnega materiala, dobro odstraniti varilsko žlindro in pred varjenjem naslednjega varka po potrebi z brušenjem razširiti in zaobliti nastale ozke in globoke medvarkovne žlebove.

Ključne besede: navarjanje, nekovinski vključki, močno pretaljevanje osnovnega materiala, pokljivost v vročem

1 INTRODUCTION

Cracks and ruptures always form due to an excessive tensile-stress concentration at the places of their nucleation due to different causes. One possible cause is the global overload of the construction. When dealing with calculated acceptable loads, an important role is played by the local-construction fatigue-notch factors and local metallurgical factors of the metal (segregation, intercrystalline impurities and brittle phases, coarse non-metallic inclusions such as slag inclusions and remains of the moulding sand, etc.). Constructional faults and metallurgical defects cause an occurrence and propagation of cracks at the stresses lower than the material's tensile strength or even the yield strength (the latter is characteristic of fatigue cracks). In this case, the construction overloading does not equal the material overloading. Due to unfamiliar metallurgical negative factors, the material overloading cannot be reliably stress determined, timed or calculated.

Among the metallurgically caused cracks there are also intercrystalline hot cracks (crystallization, liquation and polygonization cracks) that form during welding at

high temperatures (in steels at $T > 800$ °C¹). Hot cracks are a consequence of a weld and heat-affected-zone shrinkage during cooling, which, in connection with a rigid, cold surrounding environment, causes tensile stresses in the weld range.¹⁻⁵ If the deformation capacity of the metal at high temperatures during weld cooling is not sufficient, hot cracks appear because of its inability to withstand the tensile stresses at critical places (usually at the grain boundaries, contaminated with low-melting phases or eutectics of the sulphide, phosphide, carbide, boride and oxide types).¹⁻⁵ Along with the impurities (sulphur, phosphorus), the steel alloy elements of carbon, boron, niobium, nickel¹⁻⁵, titanium, zirconium and copper⁵ also increase the possibility of a hot-crack formation and, due to the possible diffusion-originated segregations on grain boundaries, chromium, manganese and silicon also have this effect.^{1,2,5} Intercrystalline segregations of sulphur, phosphorus and oxygen (oxide films) can be a consequence of non-optimum metallurgical reactions in the weld pool, but they may also occur in welds when the base material contaminated with non-metallic inclusions is remelted.^{1,2} Galaxite-oxide

films ($\text{Al}_2\text{O}_3\cdot\text{MnO}$) are often found at the crystal boundaries of the welds made from unalloyed low-carbon steels using the SAW process.^{1,2} The steels most susceptible to hot cracking are austenitic stainless steels.

This article presents the findings of a case investigation of hot cracking in the built-up tough, soft layers (an interlayer at hard facing) of a thick-walled cast (a diameter of 4500 mm, a thickness from 60 mm to 110 mm) from unalloyed cast steel with a high content of non-metallic inclusions.

2 EXAMINATION

The chemical analyses of the base material, interlayer welds and the first built-up layer (quantometer Thermo Electron Corporation ARL 3460) were made, as well as a chemical analysis and electron microscopy of non-metallic inclusions (scanning electron microscope JEOL JSM-5610 with an EDX spectrometer), macroscopy (grinding with sandpaper up to # 800, etching with Adler's reagent), optical microscopy (grinding with sandpaper up to # 4000, polishing with diamond paste of # 2 μm , etching with 2 % nital), hardness measurements, HV (device: GNEHM Härteprüfer Swiss Max 300) and the measurements of the impact toughness with ISO-V and DVM test specimens (impact testing machine AIT-300 EN). The tensile strength and yield strength could not be determined due to a lack of the material.

3 RESULTS AND DISCUSSION

3.1 Base-material analysis

The base material, on which the layers of soft steel are built-up, is a cast steel with the following chemical composition (the middle value of three analyses) in mass fractions, w/%: C = 0.30; Si = 0.37; Mn = 0.62; P = 0.023; S = 0.019; Cr = 0.16; Ni = 0.27; Cu = 0.18; Al = 0.0017. The chemical composition corresponds to grade 65–35 (ASTM A27) with the highest allowed carbon content,^{6,7} being comparable with GS-45 according to DIN 1681 (see also ⁸) or 1.0446 (EN 10027-2). The cast-steel hardness is 175 HV (the average of seven measurements), which is characteristic for a normalized condition with a polygonal ferrite-pearlite microstructure (**Figure 1a**) and the standard requirements.^{6,7} The impact toughness of the cast steel is lower (DVM: 17–26 J) than the minimum required standard value (DVM: ≥ 27 J).

A considerable quantity of non-metallic inclusions is mostly present in the microstructure of ferrite (**Figure 1a**) due to their effect on the nucleation of ferrite during the cooling of austenite from the normalization temperature. The non-metallic inclusions are unevenly distributed in the matrix, having round and angular shapes and different sizes, as stringers of isolated particles, uneven lines (**Figures 1b** and **1c**) and rosette shapes. The line- and rosette-shaped inclusions are large, their quantity is

locally very high and it is clear that they solidified from the liquid phase. The pointy angular inclusions are probably the non-molten residue of the moulding sand.

The non-metallic inclusions are sulphides and oxides. The sulphides (the examples with the chemical composition in mass fractions, w/%: Fe = 52.6; Mn = 23.7; Cr = 1.5; S = 22.2 or Fe = 5.3; Mn = 44.4; Cr = 2.3; S = 48.0) are light grey (**Figure 1c**, mark No. 1). The oxides are darker (**Figure 1c**, mark Nos. 2, 3, 4) and mostly based on iron (w/%): Fe = 95.3–97.2; O = 1.4–3.9; Ca + Cr + Mn + Si \approx 1.0). In the oxide inclusions, slightly higher contents of sulphur and phosphorus were also found (w/%): S = 0.17–0.34; P = 0.21).

Due to a combined effect of carbon and a high number of inclusions, the impact toughness of the cast steel is poor. Its susceptibility to the hot-crack formation depends on the chemical composition of steel and it is determined by calculating the index of the hot-crack susceptibility, U_{CS} . When welding the C–Mn steels with the SAW process, the following equation is used^{9–11}:

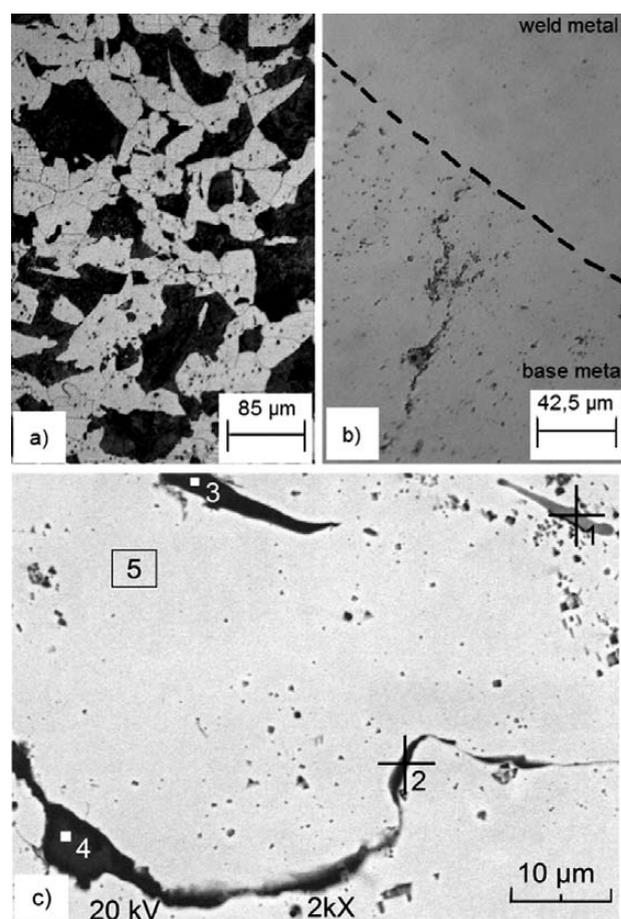


Figure 1: Microstructural characteristics of the cast-steel base material: a) normalized ferrite-pearlite microstructure with non-metallic inclusions (dark dots in the ferrite); b), c) unevenly arranged inclusions of various shapes (unetched)

Slika 1: Mikrostrukturne značilnosti navarjene jeklene litine: a) normalizirana feritno-perlitna mikrostruktura z nekovinskimi vključki (temne pike v feritu); b), c) neenakomerno razporejeni vključki različnih oblik (nejedkano)

$$U_{CS} = 230.C + 190.S + 75.P + 45.Nb - 12.3.Si - 5.4.Mn - 1 \quad (1)$$

C, S, etc. – chemical elements (w/%)

Note: at $w(C) < 0.08 \%$ the value of 0.08 is used in the equation

In general, the steels with $U_{CS} < 10$ are well resistant to hot cracking, while those with $U_{CS} > 30$ are poorly resistant. The hot cracking of fillet welds can occur at $U_{CS} > 20$ and the hot cracking of butt joints at $U_{CS} > 25$ depending on the shape of the weld pool.¹¹ Even though equation (1) was only tested with the steel-carbon content of up to $w(C) \leq 0.23 \%$ (this does not mean that the equation cannot be applied to higher-carbon contents), it was also used with the investigated cast steel for the purpose of a comparison with the added filler material. The result of the calculation shows that, due to its chemical composition, the analysed remelted cast steel has a strong tendency to hot-crack formation ($U_{CS} \approx 65.5$). A high content of oxides additionally increases the susceptibility of cast steel to hot cracking (the typical temperature at the centre of the weld pool $T = 2000\text{--}2500 \text{ }^\circ\text{C}$ ³, since the melting point of the most known oxides occurring in the metallurgy of iron and steel is $T_L < 2000 \text{ }^\circ\text{C}$ ¹²). The oxide inclusions are admixed to the weld pool and solidified at the trans-crystal boundaries.

3.2 Analysis of the built-up tough interlayers

Before hard facing in the preheated state ($T_p = (240 \pm 10) \text{ }^\circ\text{C}$) and with a controlled interpass temperature ($T_{mw} = 230\text{--}300 \text{ }^\circ\text{C}$), welding current $I = 450\text{--}550 \text{ A}$, voltage $U = 25\text{--}30 \text{ V}$ and welding speed $v = 25\text{--}30 \text{ cm/min}$, the interlayers were built up on the cast steel surface that was prepared by turning. The SAW process with the wire S2 (EN 756) and the agglomerated welding powder SA FB 1 55 AC HP 5 (EN 760) was used. According to reference¹³, the chemical composition (in vol. fractions, $\varphi/\%$) of the powder (the fluoride-based type) was: $(CaO + MgO) = 40$, $CaF_2 = 25$, $(Al_2O_3 + MnO) = 20$, $(SiO_2 + TiO_2) = 15$. When used with the S2 wire and appropriate welding parameters, this welding powder ensures the welds with the yield strength $R_y > 330 \text{ N/mm}^2$, the tensile strength $R_m = 450\text{--}550 \text{ N/mm}^2$, the impact toughness at room temperature ISO-V >

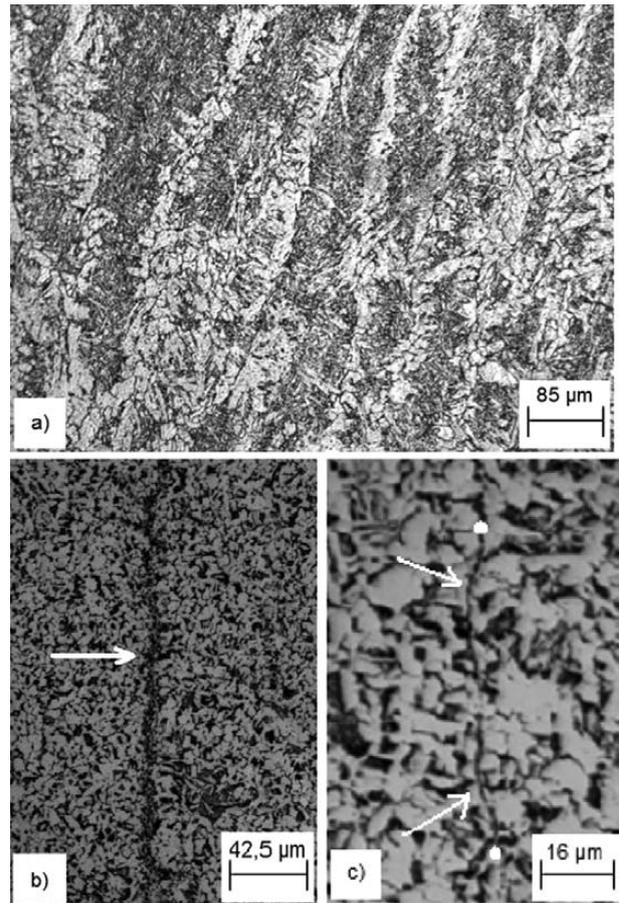


Figure 2: Microstructure of a built-up interlayer: a) the welded state, b) the normalized multi-pass region with non-metallic inclusions (arrows)

Slika 2: Mikrostruktura navarjene vmesne plasti: a) varjeno stanje, b) normalizirano medvarkovno področje z nekovinskimi vključki (puščice)

160 J, and the following deposited-metal chemical composition (w/%) : C = 0.06; Si = 0.20; Mn = 0.90.¹³ The actual chemical composition of the interlayer welds away from the base material was (w/%) : C = 0.05; Si = 0.12; Mn = 0.81; P = 0.017; S = 0.005; Cr = 0.047; Al = 0.011 and the impact toughness of the interlayer at room temperature (ISO-V: 190–203 J) justified the use of the appropriate welding materials. The interlayer consists of low-carbon steel with a typical microstructure of the used materials and welding technology. Because of the

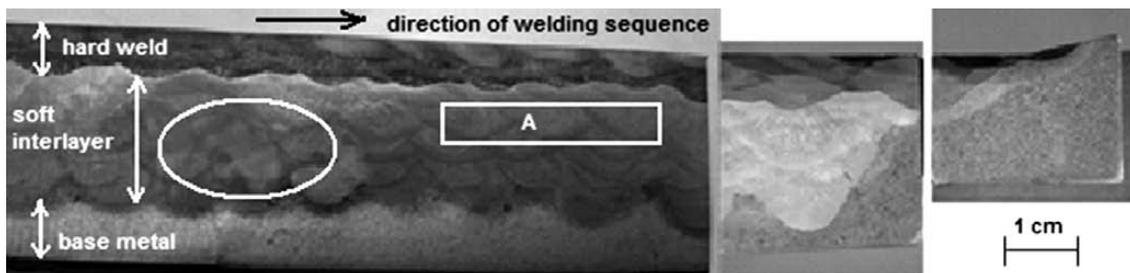


Figure 3: Cross-section through the part of a soft built-up interlayer (b. m. – base material, s. i. – soft interlayer, h. w. – hard surfacing metal)

Slika 3: Prečni prerez skozi del navarjene mehke plasti (b. m. – osnovni material, s. i. – mehka vmesna plast, h. w. – trdi navar)

multi-pass welds, the coarse columnar grains (pro-eutectoid ferrite at the grain boundaries, a fine acicular ferrite-carbide aggregate inside the grains, **Figure 2a**) and the reheated zones (a normalized ferrite-perlite microstructure, **Figures 2b** and **2c**) exist in the deposited layers.

Based on the results of the chemical analysis and the high impact toughness, it can be concluded that the used welding parameters were appropriate. All the weld metal is well resistant to hot cracking, since, according to the measured values of the chemical elements, the index of the hot-crack susceptibility $U_{CS} \approx 13.8$ is low. A problem arises when a significant quantity of the weld metal is contaminated with the base material with a high content of non-metallic inclusions and with a high content of carbon.

3.3 Analysis of the region with a built-up interlayer

The interlayer with a thickness of approximately 15 mm consisted of multilayers with a distinct wavy fusion boundary between the first layer and base material (**Figure 3**), revealing the "bead-to-bead" build-up welding technique with a minimum overlapping of the neighbouring beads. The very deep bead penetration into the base material (**Figure 4a**) caused a large admixture of the base material into the first built-up layer and the chemical composition of the first layer was (w%): C = 0.18–0.23; Si = 0.23–0.27; Mn = 0.73–0.76; P = 0.023–0.024; S = 0.019–0.021. The first beads, thus, consist of approximately 60–75 % of the base material. In the heat-affected zone (HAZ) the lines between individual beads reveal the leaning towards the outer edge of

the groove (in each layer shown in **Figure 3** they occur from left to right). During the build-up welding there were some technological difficulties. In the central part of the macroscopic pattern, an area of an uneven weld laying and unequal bead dimensions is visible (**Figure 3**, a dashed ellipse), which is a sign of grinding and redeposition in this region.

Larger cracks, visible to the naked eye, exist in the built-up layers (**Figure 4a**). Their visible length in the transverse surfacing weld is up to 3 mm (this does not mean that some cracks in the built-up interlayer are not longer). In the base material, the HAZ cracks are of a microscopic size (**Figure 4b**). Even though the U_{CS} index of the welds is small, the interlayers are more susceptible to the crack formation as a consequence of the solidification and growth of the columnar grains from the melt, due to which the impurities and low-melting phases segregate on the longitudinal boundaries of the columnar grains.

In the HAZ of the base material, the shape of the cracks depends on the shape of the non-metallic inclusions, for example, the shape of a rosette (**Figure 4b**). This is a clear indication of a melting of the non-metallic inclusions. These hot cracks are of the liquation type. Due to the non-metallic inclusions in the fusion-line region, a crack in the HAZ may propagate into a bead (**Figure 4b**). If a non-metallic inclusion is near the fusion line, this does not necessarily result in the melting of this inclusion and a crack formation in the HAZ. Liquation cracks only form when the melting point of an inclusion is sufficiently low with respect to the melting point of the base material. Such inclusions in steels are

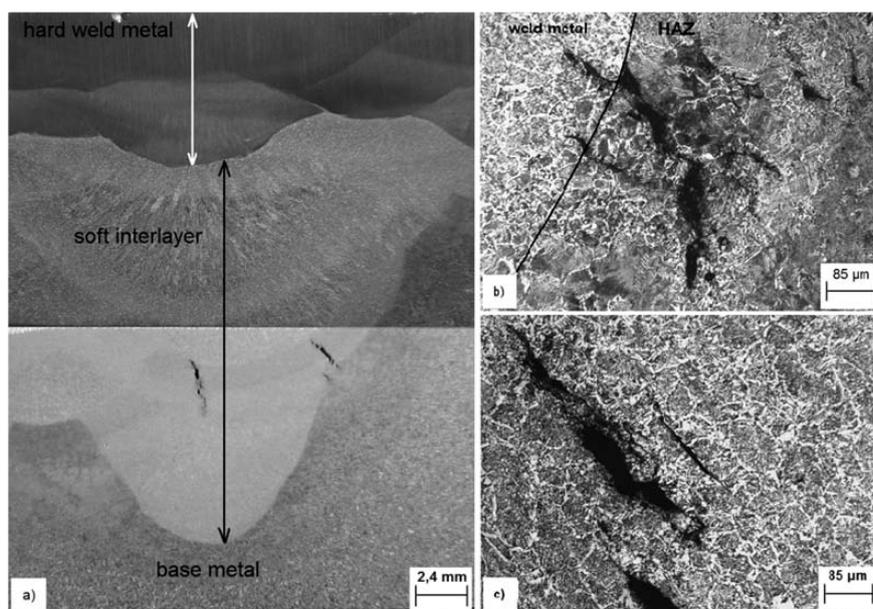


Figure 4: Hot cracks in the built-up interlayer and the base-material HAZ: a) cracks in the edge beads of the built-up interlayer, b) cluster of inclusions with the cracks in the base-material HAZ, c) cracks on the boundaries of the columnar grains in the welds

Slika 4: Vroče razpoke v navaru vmesne plasti in TVC osnovnega materiala: a) razpoke v robnih varkih navarjene vmesne plasti, b) gnezdo vključkov z razpokami v TVC osnovnega materiala, c) razpoke na mejah transkristalnih zrn v navaru

FeO ($T_L = 1377\text{ }^\circ\text{C}$) and some complex oxides, for example $\text{FeO} \cdot \text{SiO}_2$ ($T_L = 1217\text{ }^\circ\text{C}$).¹² The inclusion in **Figure 1b** did not melt because of a high melting point and though its position was next to the joining line, the liquation crack did not form. However, when the same inclusion is admixed into the weld pool, it melts due to high temperatures and can cause a solidification crack in the weld.

Cold cracks in the HAZ that would be a consequence of a brittle microstructure with a high hardness were not found. The possibility of a cold-crack formation is minimal despite a higher content of the carbon and a great thickness of the base material due to a multi-pass build-up in the preheated state and a sufficiently high interpass temperature (the low critical cooling time needed for the formation of 100 % martensite in cast steel GS-45 is $t_{cr} < 5\text{ s}$)⁸; its absence in the microstructure is proven with a relatively low hardness of the HAZ (220–270 HV).

Microscopic examinations have shown that, despite a large admixture of the base material, the first beads are already very pure in comparison with the base material (**Figure 1b**). Due to the functioning of the basic-type welding powder and the intensive melt movement during welding, a large portion of non-metallic inclusions is displaced in the slag. Inconveniently arranged intercrystalline non-metallic inclusions do not necessarily lead to a formation of solidification cracks. If the stress state is favourable, the cracks do not occur.

The cracks are only found in the welds on the edge of the prepared groove (**Figure 4a**). As the internal stresses depend on the weld shape, the formation of hot cracks in the beads on the boundary of the groove is logical due to the mutual position of the previous beads and the edge of the welding groove which causes the situation, typical for butt welds. A great stiffness due to a great thickness of the welded material causes huge transverse tensile stresses in these edge welds during cooling. In the synergy with the admixed base molten material with a large number of non-metallic inclusions and a high susceptibility to hot-crack formation, this creates the perfect conditions for the formation of hot cracks. With a 60 %

admixture of the base material, the resistance of the first beads to hot cracking is still very low ($U_{CS} = 39$, calculated from the measured chemical composition; if the index is calculated with the indexes of the base material and added material according to the rule of mixtures, it is a bit higher, $U_{CS} = 44.8$).

The crack orientation is the same as the direction of the transcrystalline growth; the cracks are situated at the grain boundaries (**Figure 4c**) and they are wide and open. The formation of the cracks is closely related to the presence of non-metallic inclusions at the grain boundaries prolonging the crack line in several places. Longitudinal inclusions are also present in the normalized HAZ between individual beads (**Figures 2b** and **2c**). Due to the normalization of this region, it seems that the non-metallic inclusions were not related to the columnar microstructure of the built-in material. However, a comparison shows that their direction is identical to the longitudinal direction of the columnar grains.

The non-metallic inclusions on the columnar grain boundaries are of very different types: iron oxides (w/%): Fe = 93.4–95.5; Mn = 0.9–1.4; O = 2.3–4.1; Ca + Si < 1) with slightly increased contents of sulphur and phosphorus (w/%): S = 0.34–0.37; P = 0.24–0.39), iron oxi-phosphides (w/%): Fe = 92.6–96.0; O = 0.5–1.1; P = 1.0–1.25; Si = 0.4–3.1; Mn, Cr, Ca: < 1,0) and more complex inclusions of oxi-sulphide (w/%): Mn = 37.0; Fe = 30.8; Si = 6.4; Al = 5.3; Ti = 1.3; S = 16.3; O = 1.9; Cr + Mg \approx 1.0) and oxi-phosphide (w/%): Mn = 31.7; Fe = 10.4; Ca = 28.7; Si = 16.7; Mg = 2.8; Al = 1.2; K = 1.2; P = 2.9; O = 3.5; Ti + S < 1.0). An inclusion of the oxi-phosphide type with numerous small surrounding inclusions and an EDX spectrogram are shown in **Figure 5** (point of measurement No. 4). Their chemical composition proves that the complex inclusions originate from the welding powder, indicating that the welding-slag-based inclusions exist in the welds, too. These can be a consequence of an inadequate welding technology and the related uncontrolled motion of the weld pool or of the remelting of the slag residue from the previously welded beads. The susceptibility of the weld pool to the formation of hot cracks is, thus, additionally increased by the liquid-slag residues. The metal matrix near the inclusion (points of analysis Nos. 1, 2, 3, **Figure 5**) has an increased content of sulphur (w/%): S = 0.13–0.28), which is probably related to the grain-boundary segregation of sulphur during solidification.

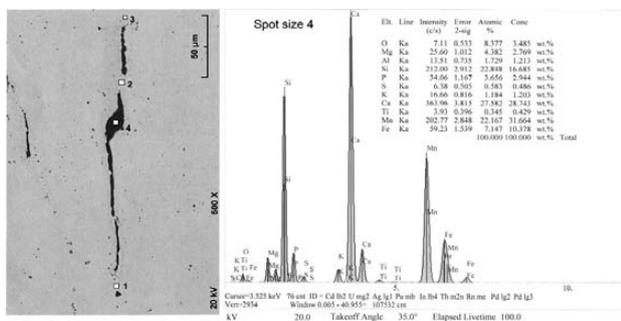


Figure 5: Complex longitudinal non-metallic inclusion in the soft interlayer weld (polished)

Slika 5: Kompleksni trakasti nekovinski vključek v navaru mehke plasti (polirano)

4 CONCLUSIONS

Low-carbon steel was built up on unalloyed cast steel 1.0446 (EN 10027-2) with the highest allowed content of carbon and a high content of non-metallic, sulphide and oxide inclusions. The cast-steel melt was, thus, very susceptible to hot cracking. Individual microscopic liquation cracks are present in the HAZ. They are related

to the sulphide and oxide inclusions. The liquation cracks in the cast-steel HAZ present a smaller problem. The cracks of a few millimetres in the individual beads of the built-up interlayer are more critical.

The use of the "bead-to-bead" build-up technique resulted in a large admixture (60–75 %) of impure cast steel and, thus, the first built-up layer was greatly contaminated with the non-metallic inclusions. In the synergy with the generated high tensile stresses, this resulted in a formation of typical crystallization cracks in the built-up layers along the base material.

The cracks are directly connected to the non-metallic inclusions of the oxide, sulpho-oxide and oxi-phosphide types on the longitudinal grain boundaries of the columnar grains. The non-metallic inclusions are mostly due to the remelting of cast steel, while some (mainly those with a complex chemical composition) are due to the welding slag. Their chemical composition is similar to the welding-powder composition (Ca, K, Mg, Al and higher amounts of Si and Mn; some of these elements are not present in the base material or pure welds, while others appear in small amounts). This reveals either local difficulties during the build-up and uncontrolled, strong and turbulent motion of the weld pool or a poor removal of the welding slag from the narrower and deeper grooves between the beads. In practice, there is a strong, but wrong conviction that because of a powerful electric arc the welding slag is easily removed from a narrow weld groove. This could be one of the reasons for the presence of complex slag inclusions in individual welds.

Hot cracks do not form if the melting volume of the cast steel with non-metallic inclusions is small. This indicates a build up with a sufficient overlapping of the neighbouring beads, ensuring the minimum thickness of the base-material remelt (when using the SAW procedure with a wire electrode, the remelting thickness of the base

material can be thinner than 2 mm). The joining line achieved in this way is practically straight and parallel with the base-material surface. The sufficient overlapping of the neighbouring beads also prevents a formation of narrow and deep grooves between the beads, in which the welding slag may be caught and not removed from the weld pool completely by the deposition of the following bead. However, if these narrow and deep grooves do occur in some places, they must be ground into sufficiently wide and rounded grooves prior to welding other beads so that the liquid slag rises to the surface of the weld pool.

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