EFFECT OF NONMETALLIC INCLUSIONS ON STEEL WELDS METAL HOT CRACKING

Intercrystally distributed nonmetallic inclusions g reatly increase weld susceptibility to hot cracking. Oxide and sulphide inclusions are the result of contaminated base material or its highly oxidised surfaces and they can be a consequence of metallurgical reactions between welding slag and remelted base material, while carbide inclusions can occur due to the mixing of high-carbon base and low-carbon Ãller material. All welding surfaces must thus be cleaned before welding and the least possible mixture of base with Ãller material must be enusured during welding.

Key words: nonmetal inclusions, dissolution of base metal, oxidized surface, hot cracking

INTRODUCTION

In welding, nonmetallic inclusions always have a negative connotation, since they increase the susceptibility of steel to hot cracking, lamellar tearing and the formation of cracks due to annealing after welding. Hot cracks are metallurgically conditioned and are caused in steels by sulphide, oxide and oxysulphide type of nonmetallic inclusions in connection with tensile stresses [1-5]. Generally these are low melting phases (e.g. melting point of FeO is $T_m = 1\,370\ °C$ [6], melting point of FeS is $T_m = 1\,190\ °C$ [3]) or low-melting eutectics (e.g. melting point of eutectic FeS – FeO is $T_E = 940\ °C$, melting point of eutectic MnS – MnO is $T_E ≈ 1\,300\ °C$ [3]) that form intercrystalline liquid films even after the crystallization of the metal matrix (in this group we also find various mixed carbide, phosphide, boride and silicide eutectics in combination with sulphur nitrogen or without them [1, 2, 7]). Oxysulphides can be globular (type I) or in the form of eutectic intercrystalline films (type II). Their shape depends on the content of oxygen in the melt [4]. Unwanted eutectic intercrystalline films (oxysulphide type II) form when the oxygen content is O < 100 ppm, while globular oxysulphides form with higher oxygen contents (O > 200 ppm). Results show that the content of oxygen must be within the boundaries O = 200 to 400 ppm [8] in order to achieve a good toughness of the weld (a consequence of acicular ferrite) as well. Thus, increased but optimal oxygen content in a weld also provides the more desirable globular shape of oxysulphide inclusions and good toughness.

A different phenomenon is the sulphide inclusion MnS with a higher melting point from that of steel (the melting point of MnS is $T_m ≈ 1\,600\ °C$ [1-3, 6]), which prevents the formation of hot cracks due to sulphur . Since MnS can intercrystally precipitate due to an eutectic reaction $L → δ + MnS$ ($T_E ≈ 1\,500\ °C$) or eutectoid reaction $δ → γ + MnS$ ($T_e ≈ 1\,350\ °C$), and because sulphide inclusions are usually of a mixed type (Mn, Fe)S, they may also increase weld susceptibility to hot cracking [2]. Hovewer, in microalloyed steels sulphide inclusions contain also zirconium, titanium and niobium, which additionally lower the melting point of an inclusion (Mn, Fe)S [1, 2].

Hot cracks can also form during weld cooling due to hard intercrystalline oxide and carbide films or a net of connected intercrystalline precipitations (e.g. carbides in stainless austenitic steels). These inclusions have very poor workability at high temperatures, thus the cohesive strength of grain boundaries is greatly reduced [1, 2, 5] since they cannot withstand the tensile plastic deformation that occurs as a consequence of rigid weld cooling. An example of this is the carbide eutectic that pours into a formed intercrystal hot crack during crystallization, and after further cooling the grain boundary cracks due to the zero deformation capacity of the carbide film [5].

This article discusses two practical examples of hot cracking that occurred as a consequence of weld pool contamination with nonmetallic inclusions, the origin of which was the welded base material. In the first example, the cause for this was severe remelting of unalloyed cast steel, greatly contaminated with nonmetallic inclusions due to the inappropriate technology of first layer build-up; in the second example, the cause was remelted unground and – due to the oxygen plasma – highly oxidized cutting surface of Hadfield steel and its mixing with the filler material of type 18Cr-9Ni-7Mn.

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INVESTIGATION

A chemical analysis of the base material and welds (quantometer Thermo Electron Corporation ARL 3460) was made, as well as a chemical analysis and scanning electron microscopy of the nonmetallic inclusions (SEM JEOL JSM-5610, equipped with EDX spectrometer Gresham Scientific Instruments, analysis performed at 20 kV), macroscopy of welds (grinding with sandpaper up to #800, etched with Adler's reagent) and light microscopy of welds (grinding with sandpaper up to #4 000, polished with diamond paste 1μm, etched with 2 % nital and aqua regia). All chemical compossotions are presented in wt. %, unless otherwise specified.

RESULTS AND DISCUSSION
### Effect of inclusions in base material

During a multilayer build-up of the intermediate ductile layer from unalloyed steel (submerged arc welding – SAW process; wire S2 EN 756 of the diameter $\Phi = 4,0$ mm; agglomerated fluoride basic welding flux SA FB 1 55 AC HP 5 at EN 760; welding current $I = 450 – 550$ A; voltage $U = 25 – 30$ V; welding speed $v = 25 – 30$ cm/min; preheating temperature $T_p = 240 \pm 10$ °C; interpass temperature $T_w = 230 – 300$ °C) onto a thickwalled cast from normalized cast steel of grade 65 – 35 at ASTM A27 (t = 60 to 100 mm; 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) hot cracks were discovered in individual beads of the first layer (Figure 1a-arrows, Figure 1b), the orientation of which was the same as the direction of transcrystal grain growth during weld pool crystallization. The cracks are intercrystalline (Figure 1b) and directly connected with the intercrystally present nonmetallic inclusions based on iron oxide (Fe = 93,4 – 95,5; Mn = 0,9 –1,4; O = 2,3 – 4,1; Ca + Si < 1; S = 0,34 –0,37; P = 0,24 – 0,39), iron oxy-phosphide (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)), as well as more complex inclusions of the sulphide-oxide (Mn = 37,0; Fe = 30,8; Si = 6,4; Al = 5,3; Ti = 1,3; S = 16,3; O = 1,9; Cr + Mg ≈ 1.0) and oxide phosphide type (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). The evidence for this is the position and orientation of nonmetallic inclusions, which in several places continue intercrystally from the crack tip in the built-up material.

Nonmetallic inclusions occur in a weld pool due to two reasons. The first one is excessive remelting of base material (Figure 1a) that is greatly contaminated (Figure 1c) with sulphide (exp. Fe = 52,6; Mn = 23,7; Cr = 1,5; S = 22,2 or exp. Fe = 5,3; Mn = 44,4; Cr = 2,3; S = 48,0) and oxide inclusions (Fe = 95,3 – 97,2; O = 1,4 – 3,9; Ca + Cr + Mn + Si ≈ 1,0). The inclusions mostly exist in ferrite due to their effect of crystal nucleuses at phase transformation $\gamma \rightarrow \alpha$. In Figure 1 ferrite is continuously formed on boundaries of former
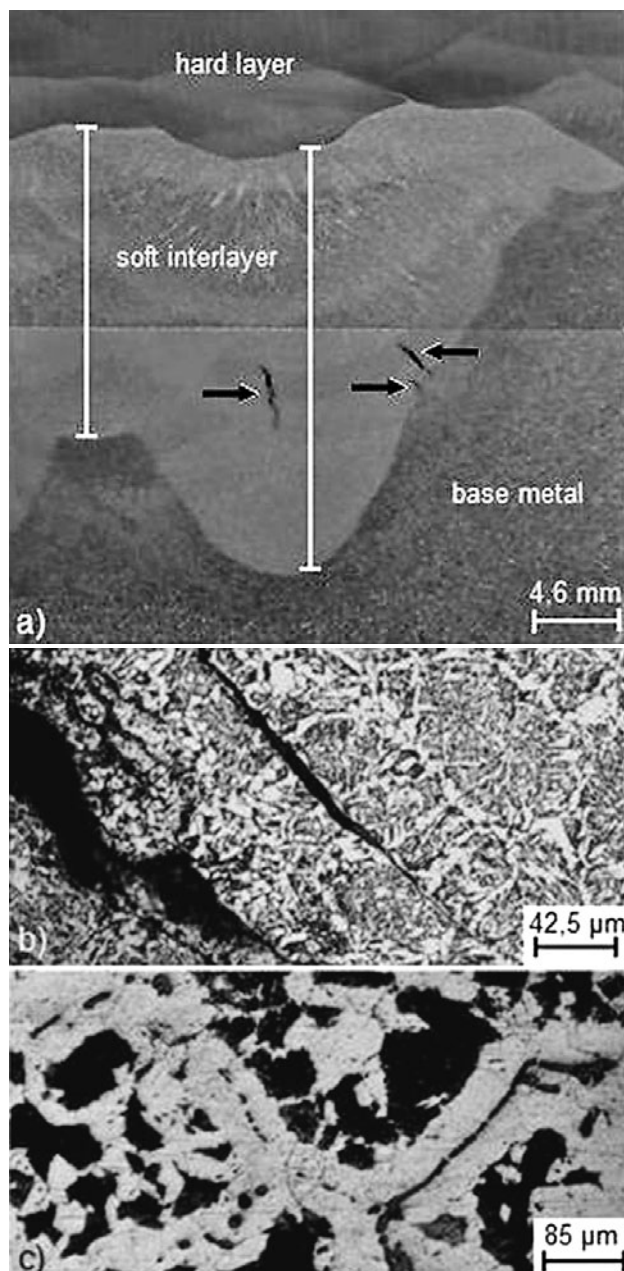
Figure 1 Characteristics of hot cracking of built-up ductile intermediate layer: (a) macroscopy of surfacing weld, (b) hot cracks on columnar grain boundaries, (c) nonmetallic inclusions in base material

austenitic crystal grains because of the intercrystalline net of sulphide inclusions that forms there. The fusion line is very corrugated as a consequence of the inappropriate »bead to bead« technique of building up (Figure 1a). Admixion of base material into the first layer is – based on the analysis of the chemical composition of all weld metal, (C = 0,05; Si = 0,12; Mn = 0,81; P= 0,017; S = 0,005; Cr = 0,047; Al = 0,01 1), the base material and first layer (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) – estimated to 60 – 75 % of base material. However, with SAW process as much as 85 % of base material can admix into the first layer [2]. The second cause for the occurrence of nonmetallic inclusions is welding flux, which is proven when comparing the complex chemical
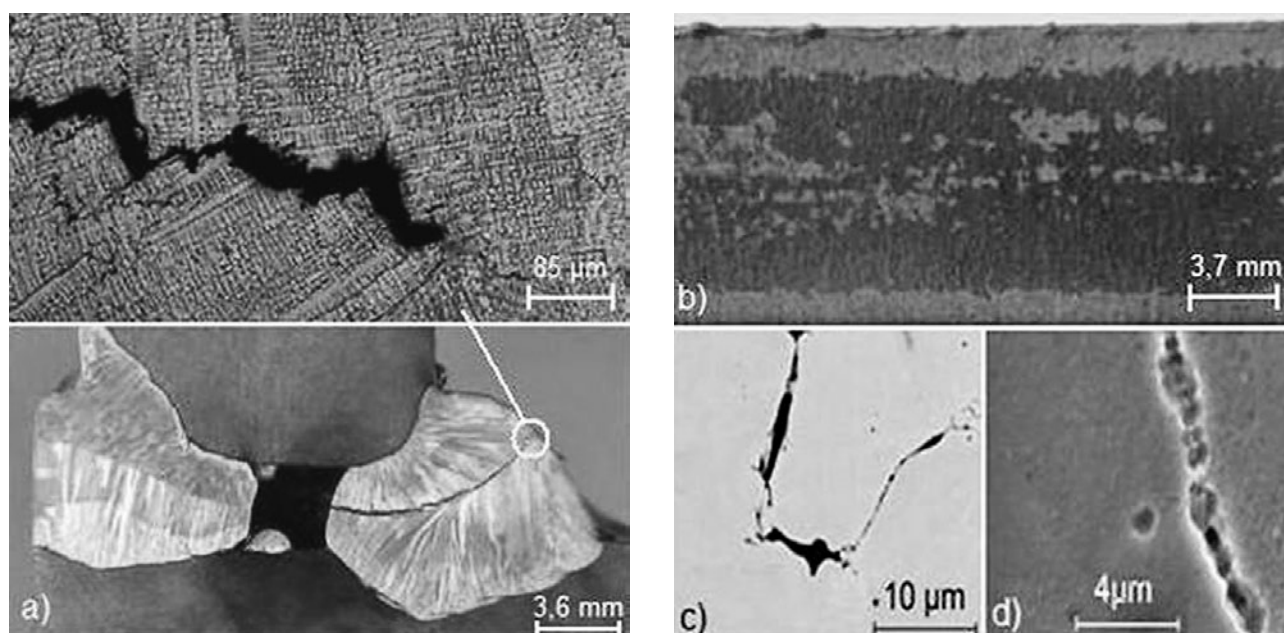
Figure 2 Hot crack in austenitic weld 18Cr-9Ni-7Mn: (a) weld macroscopy, (b) highly oxidised cutting surface, (c) intercrystalline oxide Ālms, (d) intercrystalline chain-like distribution of carbides.

composition of some nonmetallic inclusions with the chemical composition of the used welding flux (vol. %, [9]): 40 % (CaO + MgO), 25% CaF$_2$, 20 % (Al$_2$O$_3$ + MnO), 15 % (SiO$_2$ + TiO$_2$). Sulphur and phosphorus in complex inclusions prove the reaction and mixing of welding slag with remelted nonmetallic inclusions from the base material.

Susceptibility of a weld to hot cracking depends on its chemical composition and can be estimated by calculating the index of hot crack susceptibility U_{CS}. When SAW welding of C-Mn steels the following equation is used [10 – 12]:

$$U_{CS}=230C+190S+75P+45Nb–12,3Si–5,4Mn–1$$

C, S etc. – chemical elements (wt. %)

The equation is verified up to the content of carbon in steel C ≤ 0,23 wt. %.

In general, steels with U_{CS} < 10 are well resistant, while those with U_{CS} > 30 are poorly resistant to hot cracking. Between these two values hot cracking of fillet welds can already occur at U_{CS} > 20, the cracking of butt joints at U_{CS} > 25 and depends on the shape of the weld pool [12]. The investigated all weld metal is well resistant to the formation of hot cracks, since its index of hot crack susceptibility from the measured values of chemical composition equals U_{CS} ≈ 13,8. With as little as 60 % admixture of base material the index of a pure weld increases to U_{CS} = 39, meaning that susceptibility of first layer welds to hot cracking is greatly increased.

Effect of oxidized base material surface

When arc welding sandblasting chambers from 5,0 to 12,0 mm thick Hadfield austenitic high-carbon steel by using the metal active gas – MAG welding process

(chemical composition of base material: C = 1,15; Mn = 12,6; Cr = 0,5; wire diameter Φ = 1,2 mm G18 8Mn with the chemical composition: C = 0,08; Si = 0,8; Cr = 18,5; Ni = 9,0; Mn = 7,0; shielding gas Ar + 18 vol. % CO$_2$ with the flow rate 10 – 12 l/min; welding current I = 230 – 260A, welding voltage U = 28 – 28,8V, welding speed v = 28 – 32 cm/min), surface visible longitudinal central cracks were discovered in fillet welds. A macroscopic metallographic examination revealed the crack initiation in the root part of a fillet weld. From the root, where the crack was most open, it spread on the junction of both solidification fronts towards the top of a weld (Figure 2a). On the junction of the solidification fronts and its surroundings there is a large number of oxide nonmetallic inclusions, occurring in the form of an intercrystalline film (the chemical composition: Fe = 78,6 – 87,3; Cr = 4,8 – 9,8; Mn = 2,5 – 5,8; Si ≈ 0,5; O = 2,4 – 3,7; oxide inclusions are already visible in the polished state of the metallographic specimen), which indicates oxides of type FeO – Cr$_2$O$_3$ – MnO. Despite the somewhat more oxidising shielding gas (considering the filler material, the more appropriate gas would be Ar + 2 vol. % CO$_2$ or Ar + 2 vol. % O$_2$) the high content of oxide inclusions is a consequence of the remelting of highly oxidised and unclean cutting surfaces, manufactured with oxygen plasma (Figure 2b).

After etching, the fine intercrystalline mixed carbides in the form of a chain were also visible (chemical composition: Fe = 38,0 – 69,0; Cr = 9,7 – 40,0; Mn = 8,2 – 12,0; C = 9,5 – 14,2, Figure 2d; EDX analysis is not intended for a quantitative evaluation of carbon because its margin of error is too big, thus its values are only given as qualitative evidence of the chemical composition of inclusions!), the occurrence of which in a weld is a logical consequence of the mixing of high-carbon Hadfield steel with low-carbon filler material G

18 8 Mn. In this case, the hot cracks are mostly a consequence of remelted and into the weld admixed surface oxides and a secondary consequence of intercrystally precipitated chain-like carbides.

CONCLUSIONS

Intercrystally distributed nonmetallic inclusions greatly increase weld susceptibility to hot cracking. When welding steels with a high content of nonmetallic inclusions the least possible amount of their remelting and admixture to the weld pool must be ensured.This is achieved by suffi   ciently overlapping neighbouring beads and tilting the electrode or welding wire. Surfaces, intended for welding, must be cleaned of all impurities, since the weld pool highly contaminates with oxides during the remelting of highly oxidised surfaces. Welding of high-carbon austenitic steel with low-carbon austenitic filler material also requires the least possible amount of base material remelting. Severe mixing of the two materials results in carburization of the weld pool, from which chain-like fine carbides intercrystally precipitate during cooling.

Nonmetallic inclusions that occur as intercrystalline films have a lower melting point from the one of the steel matrix, thus cracks already form in the crystallization phase. Below solidus temperature intercrystally arranged nonmetallic inclusions (in the shape of films, or globular ones in the shape of a chain) greatly decrease the cohesive strength of crystal boundaries, which enables the growth of a hot crack in the interval of high-temperature brittleness (an example are intercrystally arranged FeO [13] and carbides [5]).

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