ANALYSIS OF FACTORS OF SUBSOLIDUS CRACK FORMATION IN WELDING METALS WITH FCC-STRUCTURE OF CRYSTALLINE LATTICE (Review)

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The paper gives terminological analysis of the phenomenon of subsolidus cracking in welding. Structural and technological factors affecting subsolidus crack formation in welding of various materials with fcc-structure of the crystalline lattice are considered. The need for generalizing the current concepts on this issue with application of modern physical models from the field of dislocation theory of plastic deformation and brittle fracture mechanisms at high-temperature creep is noted.

Keywords: *fusion welding, subsolidus cracks, austenitic steels, nickel, aluminium, copper alloys, terminological analysis*

In keeping with the generally accepted concepts, a separate kind of brittle intercrystalline (intergranular) fracture of weld and HAZ metal is called subsolidus cracks in welding. They initiate after completion of solidification in completely solidified metal, but at high temperatures, sufficient for predominant development of viscoplastic deformation in it [1–5]. In foreign publications, including several normative documents (DVS 1004-1, DIN 8524-3 and DIN EN ISO 6520-1), this type of hot cracks are usually called ductility dip cracks (DDC).

In terms of the widely accepted N.N. Prokhorov deformation-kinetic theory of technological strength [6–11] it is not quite correct to call hot cracks of only a certain type like that, as any cases of cracking in welding are related to the joined metal staying in the appropriate temperature range of lower ductility, so-called brittle temperature range (BTR). On the other hand, the phenomenon of an abrupt ductility drop in steels and alloys suitable for high-temperature plastic deformation during their staying in the temperature range of $(0.5–0.8)T_{\text{melt}}$ and the thus caused cracking at hot forming (forge rolling, stamping, press-forging treatment) or heat treatment has been known for many years [12–14], which is exactly what led to inclusion of the term of «ductility dip cracks» into the international welding terminology.

Despite a long-time study of the phenomenon of ductility dip or subsolidus cracks, the mechanism of their formation in welding is not completely clear yet. Proceeding from analysis of published sources, we can unambiguously state only the presence of a number of common features, characteristic of subsolidus crack formation. Numerous studies of subsolidus crack surface fractography [1, 15, 16] point to their development at high temperatures, as well as the brittle, intergranular or intercrystalline nature of fracture at the moment of initaition and growth of these defects. However, these investigations, as a rule do not give any grounds to state the presence of liquid inclusions on grain boundaries during cracking.

In addition, presence of a subsolidus brittle temperature range in a certain material, unlike the «solidification BTR», is not objectively attributable to the very specifics of the fusion welding process. While potential susceptibility to solidification cracking is demonstrated by all the structural alloys at any welding processes, as well as with some other pressure welding processes, accompanied by material overheating above the solidus temperature, initiation of subsolidus cracks requires running of special structural and phase transformation in the solid metal, the probability of which essentially depends on its composition. The most susceptible to formation of subsolidus hot cracks in welding or heat treatment are metallic materials with face-centered cubic (fcc) crystalline lattice: austenitic class steels [16–18], nickel- [2, 4, 13, 19–24], aluminium- [25], copper- [26], gold- and platinum-base [27] alloys.

Results of numerous studies of weldability of these materials point to a set of certain predominantly structural factors, influencing subsolidus cracking in welding. They include grain size, type, geometry and orientation of intergranular boundaries in relation to acting stresses, presence of precipitates of other phases, segregation of impurities or higher concentration of dislocated atoms on intergranular boundaries, as well as welding heat input and temperature rate of deformation.

Thermally activated grain coarsening increases the extent of BTR and reduces the material deformability [28, 29], and also intensifies the processes of intergranular slipping [2] under the impact of welding stresses, thus promoting crack initiation. On the other hand, the results of investigations conducted by the authors of [30] with nickel alloys of different structure and composition, do not point to the presence of a strict interrelation between the susceptibility to subsolidus cracking and base metal grain size.

Grain coarsening as a result of selective recrystallization caused by welding heat leads to straightening of intergranular boundaries. By the data of numerous sources subsolidus cracks propagate predominantly along rectilinear «flat» boundaries [2, 4, 31].

Contrarily, curvature, «waveviness» of intergranular boundary prevents slipping of neighbouring grains over it and makes crack initiation more difficult.

The role of microchemical heteromogeneity of intergranular boundaries in subsolidus crack initiation remains ambiguous and not fully understood so far. The adverse influence of intergranular boundaries contamination by such segregated impurities as sulphur [32, 33], phosphorus [33], oxygen [34] and surface-active elements such as boron, selenium etc. on their strength is a widely known fact [35]. On the other hand, alloying elements, the segregation of which along the boundaries between the grains or crystallites promotes curving of the latter, enhance the alloy resistance to initiation of subsolidus cracks. In stable austenitic steels and alloys such an effect is demonstrated by niobium [33, 36], and in niobium alloys — by zirconium and tungsten [2]. In the opinion of the authors of [33], alloying of austenitic alloys by elements with atomic radius greater than that of elements of the solid solution base (iron, chromium, nickel), leads to suppression of selective recrystallization and promotes curving of intergranular boundaries, which is favourable for weld metal resistance to subsolidus cracking.

Assessment of the role of hydrogen dissolved in the weld metal in initiation of intergranular cracks of subsolidus type is a subject for a separate discussion. Despite the high solubility and relatively low rate of atomic hydrogen diffusion in a crystalline structure with fcc-lattice, some cases of failure of welded structures made from copper, aluminium or nickel alloys due to hydrogen embrittlement or the so-called hydrogen disease of welded joint metal are known from practical experience [37–40]. Investigation of weldability of a number of nickel alloys showed that the destructive action of hydrogen is not limited to the known cases of corrosion cracking, for instance, of nuclear reactor primary circuit steam piping. So, by the data of [41], increase of hydrogen concentration in shielding gas composition in welding a number of alloys of Ni–Cr–Fe system causes an essential lowering of weld metal resistance to subsolidus crack initiation. Fractographic analysis of crack surfaces, in addition to flat nature of fracture, also revealed individual cavities, similar to micropores [42].

Increased susceptibility of dispersion-hardening nickel alloys to formation of subsolidus cracks in welding and heat treatment made several researchers look for causes for these defects development in the processes of coagulation, or dissolution and re-precipitation, predominantly along the boundaries between the grains and crystallites, of strengthening phases, present in the structure of these alloys, namely carbides and γ'-phase of $Ni_3(Al, Ti)$ type. According to [43, 44], subsolidus cracks initiate on the boundary between the phase and grain of the solid solution as a result of higher concentration of stresses in these regions, thus causing formation of microprotrusions and their further opening into cracks during intergranular slipping under the impact of temperature stresses. Taking into account the results of processing numerous crack resistance tests in [45, 46], it is proposed to assess the nickel alloy susceptibility to subsolidus cracking, depending on their content of the main γ'-forming elements, namely aluminium and titanium. It is assumed that in alloys with a low intensity of dispersion-hardening, when the overall content of aluminium and titanium does not exceed 3–4 %, formation of subsolidus cracks during their processing in welding is improbable.

A similar opinion is expressed by the authors of [47]. Studying crack resistance of Ni–20–30 % Cr alloys, they put forward the hypothesis that the cause for subsolidus cracking in welding of these materials is contribution of additional stresses localized along grain boundaries to macroscopic action of welding stresses. These additional stresses are due to thermal ageing of the alloys with the resulting precipitation along the grain boundaries of carbide particles of the type of $(Cr, Fe)_{23}C_6$, partially coherent with the matrix crystalline lattice. Here it is stated that these are exactly the partially coherent precipitates of $(Cr, Fe)_{23}C_6$ carbides, that cause the appearance of local elastic stresses along the boundaries between the matrix grains and carbide phase particles. Non-coherent precipitates of carbides of MeC or Me_7C_3 type do not show such an effect.

On the other hand, there are numerous publications, in which the «carbide hypothesis» of subsolidus crack initiation is disproved. In [22] it is shown that the carbides distributed along the intergranular boundaries prevent boundary straightening during recrystallization and, thus, complicate the intergranular slipping and crack formation. This viewpoint is confirmed by the results of microstructural investigations [30] of the edges of subsolidus cracks formed in welds of a number of nickel alloys. It is shown that the carbide precipitates along the boundaries inhibit crack propagation instead of initiating it. More over, in [30, 48] it is established that in a number of alloys subsolidus cracks form in the high temperature range, when the carbide phase is completely dissolved or is present in an extremely insignificant amount.

A well-grounded view point on the role of $Me_{23}C_6$ type carbides and γ'-phase in formation of subsolidus cracks is given in [49, 50]. Authors of these studies showed for various dispersion-hardening nickel alloys that a local decrease of ductility of these materials under the action of welding heat is due to diffusion redistribution between the grain and intergranular boundary of alloying elements involved in formation of the carbides and γ'-phase. As a result, in the near-weld zone near the fusion line the boundary grain portions are softened because of their depletion in γ'-phase, while grain boundaries are enriched in carbide precipitates and particles of surface-active impurities. As a result, the difference between the values of strength of intergranular boundary and grain (near it) takes critical values, this being exactly what simplifies formation of subsolidus type cracks during intergranular slipping.

Practically all the researchers of the problem of subsolidus cracks in welding of polycrystalline materials are of the opinion that development of this type of intergranular fracture occurs predominantly along the boundaries located at an angle of 45–90° relative to the weld longitudinal axis [2, 3, 27, 36, 41]. This fact is in good agreement with the decisive role of the process of intergranular slipping in subsolidus crack initiation, during which these are exactly the grain boundaries located at an angle of 45–90° to the direction of longitudinal welding stresses that are exposed to the action of maximum cleavage stresses.

In addition to the «macroscopic» spatial orientation of grain boundaries relative to the direction of the action of welding stresses, crystallographic orientation of neighbouring grains also has a certain role in subsolidus crack initiation. As is known, the angle of mismatch of crystalline lattices of the neighbouring grains determines the potential energy of the boundary between them, and, thus, the degree of its saturation with impurities. This leads to different crystallite boundaries demonstrating different deformation resistance, which, in its turn, leads to non-uniform distribution of intercrystalline deformation in welding. By the data of [2, 31], the most intensive intergranular slipping and formation of subsolidus cracks occur along the strongly disoriented, so-called regular boundaries, along which the angle of mismatch of spliced crystalline lattices is greater than 15°. The above-noted is confirmed by experimental studies on the influence of the type of intergranular boundaries on the susceptibility of metal of high-temperature nickel alloy welded joint to formation of subsolidus cracks conducted by the authors of [23]. More over, application of special stepped thermodeformation treatment of base metal before welding, which increases the volume fraction of special low-angle boundaries with a low level of free energy, allowed a considerable increase of the material ductility margin within the anticipated subsolidus BTR.

Welding heat input is a generally known technological factor of controlling welded joint metal susceptibility to hot cracking of all types. According to numerous recommendations [27, 43, 44, 51] reduction of heat input causes a narrowing of subsolidus BTR, increase of the metal ductility margin within BTR and, thus, is a rational technique for subsolidus crack prevention. As welding heat input is inversely proportional to the rate of cooling of welded joint metal, the positive effect of reduction of the heat input is most often attributed to reduction of the time of the metal staying in the range of temperatures of predominant development of intergranular plastic deformation. For instance, by the data of [27], the intensity of intergranular slipping is linearly dependent on the time of the metal staying in the high temperature range. In welding of nickel alloys, forced cooling is sometimes used for an effective reduction of this parameter and prevention of cracks in the near-weld zone [52].

Unlike the welding heat input the role of deformation increase rate in subsolidus crack formation is described in publications in a somewhat contradictory manner. The authors of [53], proceeding from the proportionality of the cooling rate to deformation rate in welding, note that decrease of deformation rate increases the intergranular slipping and promotes formation of subsolidus cracks. Similarly, by the data of [44], deformability of welded joint metal within the subsolidus BTR, increases at increase of deformation rate.

On the other hand, work [2] states the opposite — with increase of deformation rate the critical velocity of integranular slipping, sufficient for subsolidus crack initiation, decreases.

Thus, proceeding from the conducted analysis of factors of subsolidus crack formation in welding of austenitic steels and alloys, we can note their diversity and ambiguous, based on different published data, nature of their influence. On the other hand, proceeding from the intergranular nature of local fractures, which subsolidus cracks are in polycrystalline materials, it is obvious that intercrystalline plastic deformation in the form of intergranular slipping has the decisive role in their initiation.

In addition to intensive slipping of neighbouring grains, the following should be also regarded as the necessary conditions for subsolidus crack formation: stress localizing along the individual grain boundaries, non-uniform deformation of boundary portions of grains, weakening of intergrnular boundaries and adjacent grain portions by the specific nature of structural and phase transformation in welding and gradual accumulation of submicrodefects — crack nuclei — near the submicrodefect interface. This, in its turn, allows projecting the known physical models of brittle fracture of metals and alloys at high-temperature creep on the mechanism of subsolidus crack initiation in welding or heat treatment of welded joints.

CONCLUSIONS

1. Subsolidus cracks, proceeding from the totality of features, such as brittle intergranular (intercrystalline) nature of fracture, as well as temperature-time range of formation (below the solidus temperature, but above $(0.5–0.8)T_{\mathrm{melt}}$), initiate directly under the influence of thermodeformational cycle of welding on

the material and are a separate subtype of hot cracks in welding.

2. Increased susceptibility to formation of subsolidus type cracks is found in metals and alloys with fcc-lattice and absence of allotropic transformations.

3. Influence of the following structural and technological factors on subsolidus cracking is the best studied: grain size, type, geometry and orientation of intergranular boundaries relative to the acting stresses, presence of precipitates of other phases on the intergranular boundaries, chemical inhomogeneity, as well as welding heat input and temperature rate of deformation. On the other hand, the influence of these factors has not been generalized, and by the data of various publications it is sometimes contradictory.

4. Necessary conditions for initiation of subsolidus cracks are intercrystalline plastic deformation in the form of intergranular slipping and stress localizing along the individual grain boundary portions, weakened by the specific nature of structural and phase transformations in welding. In order to construct a generalized physical model of subsolidus cracks, it is necessary to involve the modern concepts from the field of dislocation theory of plastic deformation and mechanisms of brittle fracture at high-temperature creep.

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