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A New Look at the Classification of Cracks in Welded and Braze Welded Joints

Abstract: The making of structures using advanced materials and joining technologies is frequently accompanied by limited weldability problems. The obtainability of joints characterised by required properties can be limited, among other things, by susceptibility to crack formation. The article presents an overview of classification of cracks in welded and braze welded joints based on reasons for crack formation and the period of crack development. The primary division of fabrication/production-related cracks includes hot, cold, lamellar and annealing cracks. The study recommends the extension of the above-presented classification by including cracks occurring at a temperature higher than ambient temperature and lower than the lower limit of high-temperature brittleness range. The above-named temperature range could include cracks triggered by the loss of plasticity in the solid state resulting from the occurrence of ductility-dip brittleness and cracks related to liquid metal embrittlement.

Keywords: fabrication-related cracks, production-related cracks, ductility-dip brittleness, liquid metal embrittlement

Introduction

Weldability is one of the key features of metallic materials enabling the obtainment of stable joints characterised by appropriate functional characteristics. In turn, one of the major issues related to the metallurgical aspect of weldability is susceptibility to the formation of various cracks.

The crack can be defined in several various ways. The PN-EN ISO 6520-1 standard describes the crack as a welding imperfection following the local rupture in the solid state, triggered by cooling or stresses. The issue of the cracking of welded joints has been known for a long time. In one of the first issues of the Polish journal Welding and Cutting of Metallic Materials (no. 7, published in 1928), the article entitled On Acetylene Welding and Welding Imperfections indicated that primary welding imperfections included, among other things, a "surface crack" [1].

In reference publications of the time it was also possible to come across other terms. The 1950s saw the usage of the term of "scratch" describing a crack which did not develop right through and did not form a wide gap [2]. Cracks were divided into internal and surfacing cracks as well as longitudinal and transverse in relation

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to the weld axis. It was then claimed that cracks were formed as a result of contraction and the partial martensitic transformation of the base material [2, 3]. At the turn of 1970s there was a division including super-solidus (hot) and sub-solidus (cold) cracks. It was also observed that stress-relief annealing could lead to the formation of cracks in the HAZ [4]. The division used in 1980s included hot, cold and lamellar cracks as well as cracks formed during the post-weld heat treatment [5, 6].

The progress in testing methods and the growing understanding of phenomena occurring in materials subjected to welding has encouraged the more detailed analysis of reasons for crack formation and the period at which cracks are initiated and undergo propagation. The foregoing has led to the identification of two primary types of cracks, i.e. cracks related to production/fabrication (technological,

efficiency-related) and operation-related cracks.

Classification of crack types

Production/fabrication-related cracks constitute a group of cracks which are initiated and develop during or directly after the welding process, i.e. when a joint is not yet exposed to operating conditions (loads, forces, moments, pressure, corrosion etc.). This group of cracks includes four primary types of cracks, i.e. hot, cold, lamellar [5-10] and annealing [5-9]. It is usually assumed that hot cracks occur at a temperature exceeding the half of the melting point value, whereas cold cracks are formed below the above-named temperature, after the transformation of cooled austenite into martensite/ or bainite. Lamellar cracks are usually formed at a temperature below 200ºC and tend to result from the contraction of welds intensified by the stiffening of a joint. In turn, annealing

Table 1. Division of cracks in relation to occurrence and reasons

Based on publication [8]			
Technological cracks			
Hot	**Cold**	**Lamellar**	**Annealing**
solidification cracks in the weld, segregation cracks in the HAZ.	cracks triggered by martensite brittleness, hydrogen-induced cracks.	classical cracks.	low-temperature cracks, high-temperature cracks, sub-clad cracks.
Operation-related cracks			
Brittle cracks		Fatigue cracks	

Based on publication [11]			
Production-related cracks			
Hot	**Warm**	**Cold**	**Other**
solidification cracks in the weld, segregation cracks in the HAZ, segregation cracks in the weld.	annealing cracks, strain-age cracks, cracks related to: loss of plasticity at high temperature, liquid metal embrittlement.	post-weld cold cracks, hydrogen-induced cracks.	production-related cracks connected with welding imperfections, cracks related to metallurgical anomalies (e.g. local fatigue or brittleness).
Operation-related cracks			
hydrogen-induced cracks, corrosion-related cracks, relaxation cracks,		fatigue cracks, creep-related cracks, mechanical overload-related cracks.	

cracks are triggered by post-weld reheating. The above-named division is justified in cases of conventional weldable steels used in structures exposed to standard operating conditions. As new steel grades are launched and increasingly high operating conditions-related requirements follow, it appears justified to extend the primary classification by including specific cases of basic cracks [8] or even by separating and creating a new group of cracks [11]. The detailed analysis of related reference publications indicates examples of such an approach (presented in Table 1). The proposal of the division of cracks presented in publication [11] led to the conclusion that, apart from hot and cold cracks, there should also be a new group of cracks referred to as warm cracks and a group of other cracks not assignable to any of the previously specified groups.

Warm cracks

Warm cracks ("quasi-hot cracks") belong to cracks initiated at a higher temperature in the solid state (in the weld and/or HAZ) and are tied primarily to phenomena occurring on grain boundaries. The group of warm cracks includes annealing cracks, strain-age cracks as well as cracks related to the loss of plasticity at a higher temperature and liquid metal embrittlement. Warm cracks are formed within a range between slightly below the solidus line and the temperature of supercooled austenite transformation or the melting point of the metallic material present in the fabrication process and characterised by the lowest melting point.

Annealing and strain-age cracks

Annealing cracks are formed or propagate during annealing after welding at a temperature below A1 and are usually nucleated in the coarse-grained heat affected zone. A significant welding rate restricted within the range of 200 °C to 300°C could result in the significant gradient of temperatures between the surface and the centre of an element and, consequently,

lead to the generation of thermal stresses which, combined with welding stresses, lead to the exceeding of the material strength manifested by the formation of cracks. Annealing cracks can also be formed at a higher temperature during the stress relaxation of steels containing chemical elements providing the effect of secondary hardness during the heat treatment (i.e. Mo, Nb, V, Ti). The process of heating up to and reaching the annealing temperature is accompanied by the precipitation of carbides (ε, M2C, MC) responsible for material hardening. Because of the faster diffusion of chemical elements along the grain boundaries, precipitates located in the aforesaid area are larger, whereas adjacent areas are characterised by the reduced content of carbide-forming elements. The presence of precipitate-free zones formed in the above-presented manner leads to the significantly lower hardening of the material. The aforesaid difference in mechanical properties is responsible for the fact that, during heating, the yield point of precipitate-free zones decreases faster and is the first to reach the value of welding stresses, leading to the relaxation of stresses through the plastic strain of areas characterised by a small specific surface area, incapable of transmitting such stresses and, consequently, resulting in the formation of a crack [8, 11-13].

Strain-age cracks, because of their analogous cracking mechanism, often classified as annealing cracks, are characteristic of welded joints made of nickel alloys subjected to heat treatment involving solutioning and ageing. The slow heating-to-solutioning process is accompanied by the relaxation of welding stresses as well as precipitation, where precipitates on grain boundaries are larger than those inside grains. The near-boundary areas contain precipitate-free zones, which, because of their lower yield point, constitute areas where the relaxation of welding stresses take place through plastic strains. Because the process of cracking occurs during the ageing of alloys, it is referred to as strain-age cracking [11, 12].

The last specific case of annealing cracks includes the so-called "sub-clad" cracks formed during the cladding of unalloyed steels with strips made of austenitic alloy steels. Such cracks are also found in the coarse-grained HAZ area heated by a successive thermal cycle to a temperature below A1. The high crack-initiating level of welding stresses is induced by the high difference of linear expansion coefficients. In terms of austenitic steels, the above-named difference is 1.5 times higher than that in relation to unalloyed steels [8].

Ductility-dip brittleness

The loss of plasticity at a higher temperature occurs in relation to many engineering materials including austenitic steels, nickel alloys, aluminium alloys, copper alloys or titanium alloys. The above-named phenomenon was known at the beginning of the 20th century,

yet initially it was related to the deformation of bar or sheet/plate ingots. Although in welding engineering the problem of cracking is believed to have been identified in 1970s and 1980s, it was addressed significantly much earlier but mistakenly interpreted as a form of hot cracks or microcracks. Ductile-dip cracks (DDC) occurring within the ductility-dip temperature range can be formed both in the weld and in the HAZ, yet the problem is believed to primarily concern welds, particularly those reheated in multi-run welding processes. The range of a decrease in plasticity is schematically presented in Figure 1a. The range identified in relation to weld deposit NiCr30Fe9 is presented in Figure 1b, whereas that in relation to the welds made of steel 7CrMoVTiB10-10 is presented in Figure 1c. The cracking mechanism and factors affecting susceptibility to cracking have not been entirely identified yet [11, 14-16].
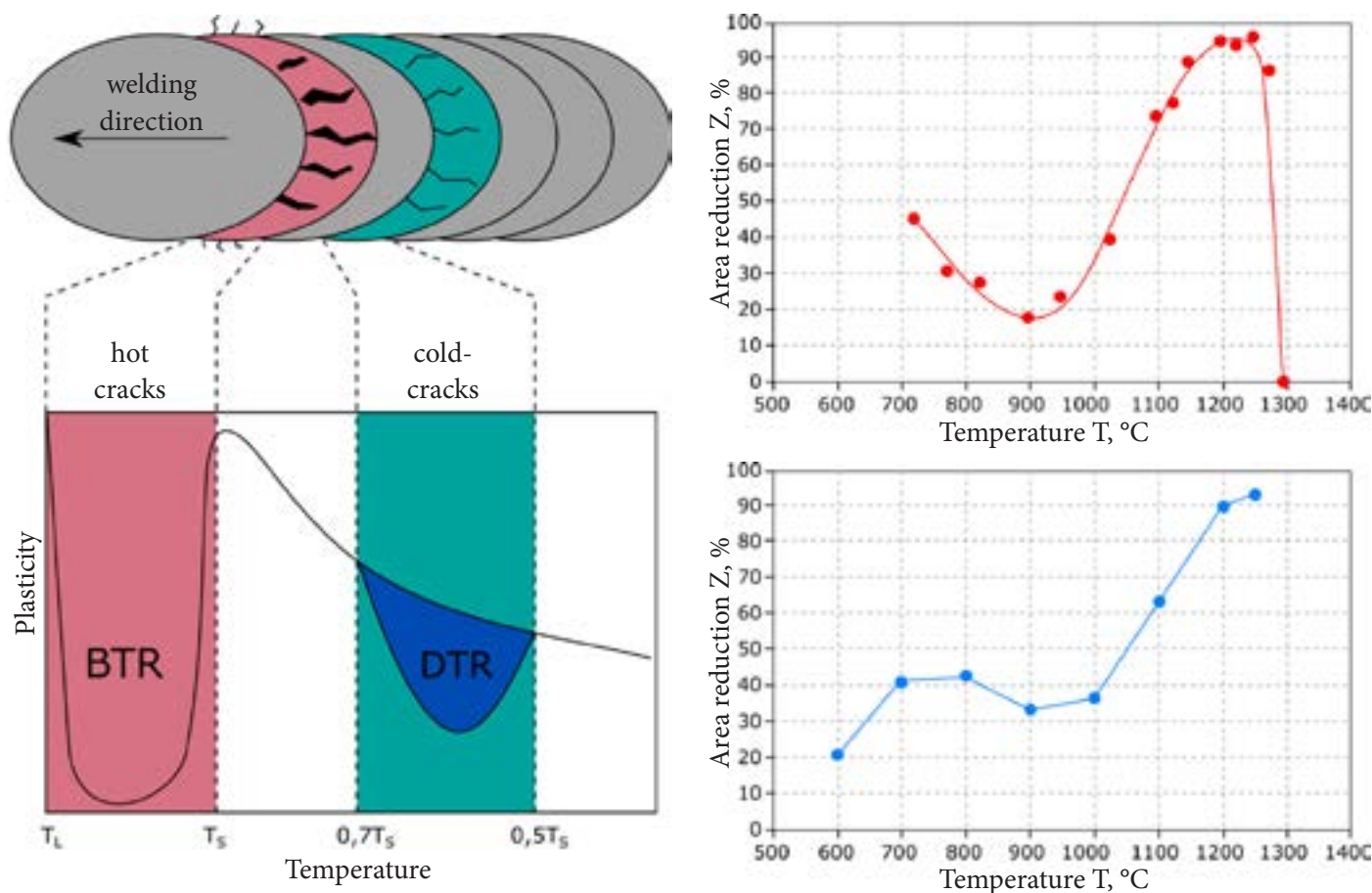

Fig. 1. Dependence of plasticity on temperature in relation to alloys susceptible and non-susceptible to ductility-dip brittleness: a) schematic diagram according to [14], b) range in relation to weld deposit NiCr30Fe9 [15], c) range in relation to the welds made of steel 7CrMoVTiB10-10 [16]

Liquid metal embrittlement

Liquid metal embrittlement (LME) is manifested by a decrease in the plasticity and crack resistance of a material subjected to stresses and the direct contact with liquid metal. As a result of the wetting and penetration (along grain boundaries) of a material characterised by a higher melting point by a liquid material characterised by a lower melting point, leading to a decrease in the cohesive strength of grain boundaries and an increase in shear strains, cracks are of intercrystalline nature. The formation of a crack requires the low mutual solubility between a solid-state material and a liquid-state material, the impossibility of intermetallic phase formation and the formation of a barrier to the plastic strain along grain boundaries [11, 17].

In terms of steels, the most common liquid metals triggering the formation of cracks include copper, zinc, lead and mercury, usually coming from copper clamps, backing strips, fixtures, contact tubes and nozzles coming into contact with a welded material heated to a high temperature as well as copper, zinc or lead coatings deposited on products before welding [11, 17]. Figure 2a presents an exemplary crack, the source of which was the zinc coating. As a result of a heat input accompanying the welding process the coating melted. In turn, the stiffening of the structure resulted in the exceeding of a critical stress triggering the penetration of liquid zinc along grain boundaries [18]. Figure 2b presents cracks in an arc braze welded joint made using a copper-based wire. The cross-section subjected to analysis revealed between ten and twenty areas penetrated along grain boundaries by liquid copper [19]. The LME-type crack can also be formed as a result of an increased copper content in the base material (e.g. alloy steel). Figure 2c presents the cross-section of an autogenously welded joint made of steel X5Cr-NiCuNb16-4 (17-4PH), containing between 3 and 5% of copper. The source of the enrichment of the steel surface in copper could be the

intense evaporation of copper from the weld pool and its subsequent deposition triggered by the shielding gas recirculating copper vapours to the HAZ surface [20].
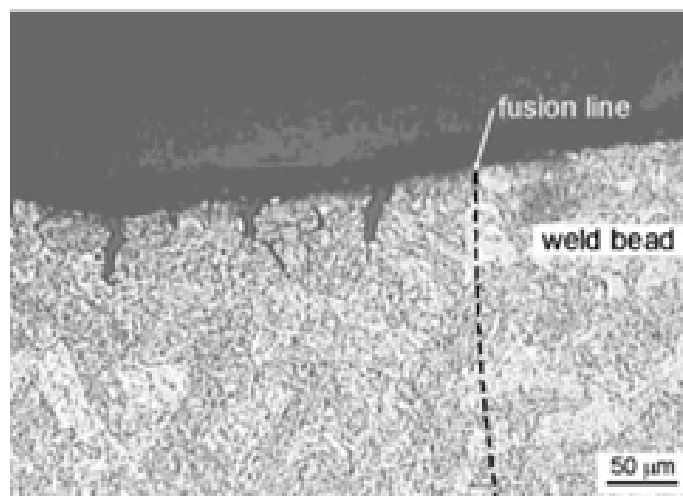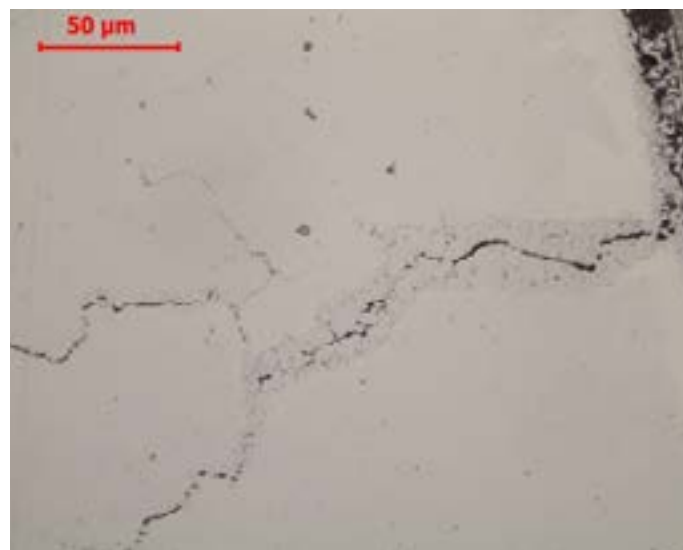

Fig. 2. Cracks triggered by liquid metal embrittlement: a) zinc from the zinc coating on the sheet surface [18], b) copper from the weld deposit [19], c) copper from the material being welded [20]

Summary

Cracks belong to some of the most hazardous and, at the same time, unallowed welding imperfections. The detection of cracks in welded joints necessitates their repair or, frequently, the scrapping of the entire product. The continuous development of testing methods enables the increasingly good identification of crack initiation sources and, consequently, makes it possible to apply necessary preventive measures. Taking the above-presented analysis into consideration it seems advisable to elaborate the classification of production/fabrication-related cracks by adding warm cracks including annealing cracks, strain-age cracks as well as cracks triggered by ductility-dip brittleness and liquid metal embrittlement.

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