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Research Article

Determination of the Effective Microstructural Unit in Relation to the Weld Metals Brittle Fracture Resistance

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Abstract

Metallographic studies of the high-strength, low-alloy steels weld metal structure show that the cracks in the structure can pass through several grains, or stop at the grain boundary or in the middle of the grain. Resistance to weld metal brittle fracture is usually associated with the grain size in its structure. Recently, works have appeared in the scientific and technical literature, in which instead of grain sizes, that is, the solid solution region delineated by the phase boundary, it is proposed to determine the influence of the solid solution region with a close orientation of ferrite formations. Purpose of the article: To clarify the grain size definition for the welds metal structure. Recently, works have appeared in the scientific and technical literature, in which instead of grain sizes, that is, the solid solution region delineated by the phase boundary, it is proposed to determine the influence of the solid solution region with a close orientation of ferrite formations. Key Idea: For weld metal, the structural grain size is determined by the disorientation index at the grain boundary. The article presents a critical analysis of the authors results concerning the point of view on the validity of such an approach to assessing the influence of microstructure on the metal of welds mechanical properties. Conclusion: When analyzing the weld metal structure influence on the mechanical properties, the grain size must be determined using the disorientation parameter at the grain boundary.

Keywords

Weld Metal, Low-Alloy Steel, Microstructure, Crystallographic Grain Orientation, Mechanical Properties of Weld Metal

1. Introduction

High-strength, low-alloy steels are widely used in the manufacture of welded structures due to the weld metal strength, plasticity and viscosity combination. The further growth of the low-alloy rolled products mechanical properties complex determines the research relevance on the welds microstructure influence on the weld metal mechanical properties.

Development peculiarities of the low-alloy steels destruction under static loading, intergranular spelling and under low temperatures conditions processes were discussed at several specialized seminars by of the IMF named after G. V. Kurdyumov and IEW named after E. O. Paton of the Ukraine Sciences National Academy specialists and summarized in a monograph [1]. The metal mechanical properties are usually associated with the grains size in its structure. It is this approach that is used in technological processes aimed at increasing the metal viscosity due to the grinding of the grain size in the ferrite-pearlite steels structure, but in relation to ferrite-bainite and bainite-martensitic steels, certain peculiarities in the nature of such an effect were revealed due to their complex hierarchy in morphology and crystallography [2, 3].

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Recently, works have appeared in the scientific and technical literature, in which the expediency of using another microstructural unit for evaluating the resistance to metals brittle fracture is substantiated [4, 5]. Instead of grain sizes, i.e., the solid solution region delineated by the phase boundary, it is proposed to determine the solid solution region influence with a close orientation of ferrite formations.

A critical analysis of the authors research carried results out from the point of view on the validity of such an approach to assessing the microstructure influence on the welds metal mechanical properties of low-alloy steels is presented in the above article.

2. State of the Problem

One of the main indicators for evaluating the both mechanical properties low-alloy high-strength steels and the weld joints is the structural elements (grains, subgrains, phases, inclusions, etc.) size.

It is well known that the structural steels strength, fracture resistance, and the plastic-brittle transition temperature obey the typical Hall–Petch relationship. The yield strength is given by the classical Hall–Petch relation:

$$\sigma_\psi = \sigma_0 + K_\psi d^{-1/2} \tag{1}$$

where d is the average grain size and K_ψ is the Hall–Petch coefficient for strength.

The chipping type fracture stress can be described by the formula

$$\sigma_f = K_f d^{-1/2} \tag{2}$$

where K_f is the Hall–Petch coefficient for chipping.

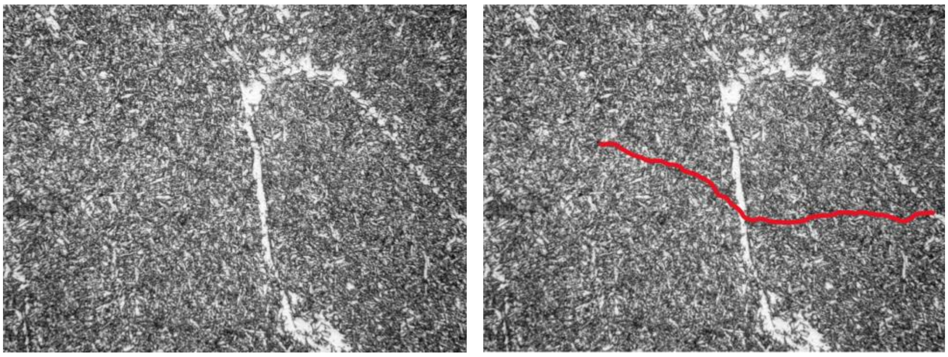
The plastic-brittle transition temperature is often subject to the equation

$$T_B = T_0 K_B d^{-1/2} \tag{3}$$

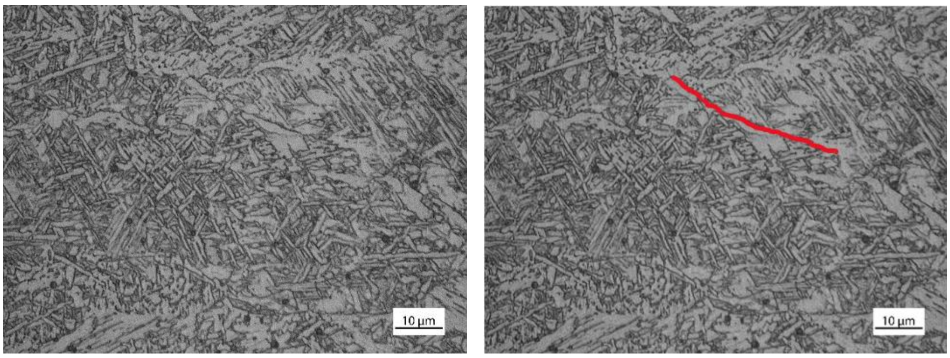
where K_B is the corresponding Hall–Petch coefficient.

Expressions 1-3 use different coefficients (K_ψ, K_f, K_B) that correspond to different physical destruction processes. Due to the fact that the same parameter, grain size, d, appears in each of these equations, it is important to determine which grain should be taken into account.

Metallographic studies of the high-strength, low-alloy steels weld metal structure show that the cracks that originated in the structure can pass through several grains (Figure 1a), or stop at the grain boundary (Figure 1b) or in the middle of the grain (Figure 1c). That is, to evaluate the grain characteristics effect on the metal mechanical properties in accordance with expressions 1-3, the indicator d in some cases coincides with the grains size that have a allotriomorph ferrite rim, and in others it is necessary to use the a certain grains block size. This crack type development is associated with the weld metal bainite polycrystalline structure formation features.



a)



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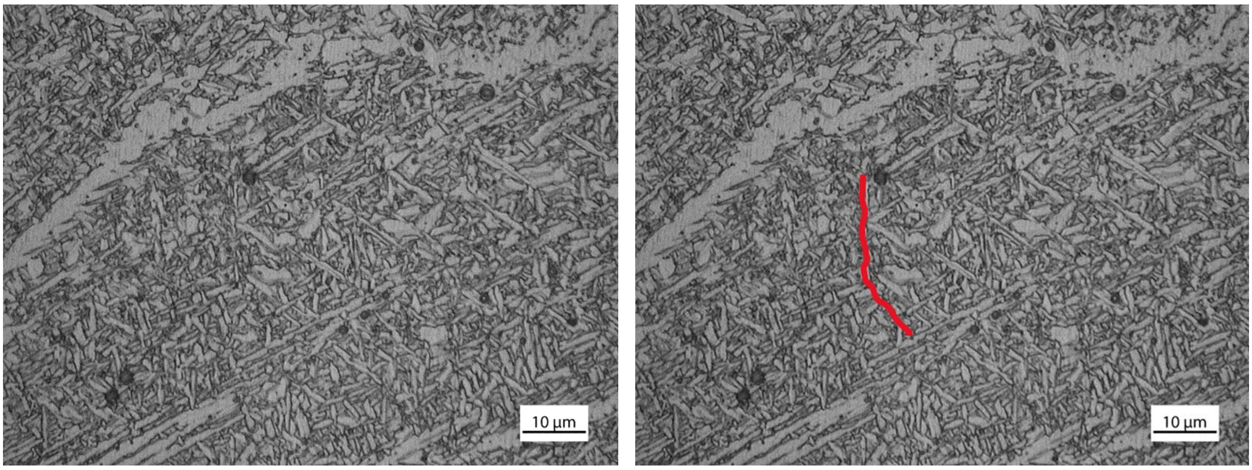

c)

Figure 1. *The low-alloy steel weld metals microstructure samples containing cracks: a) X200, b), c) X1000.*

Cracks are indicated in red: a) Crack pass through several grains; b) Crack stop at the grain boundary; c) Crack do not go beyond the grain boundaries

It is well known that bainite is a microstructure that forms during austenite transformation at moderate cooling rates. Bainite, as an austenite intermediate transformation structure, has both signs of diffusion (pearlite) and non-diffusion (martensitic) transformation. As a result, the bainite structure consists of parallel plates packages in the so-called "morphological package". The good viscosity of this microstructure is due to the high-angle boundaries high density that these microstructures usually have. Ferrite structures formed as a bainite transformation result make up a significant part of the high-strength low-carbon steels weld metal microstructure. The balance between a metal the strength and viscosity largely depends on the structural grains size, the dislocations density, the small cementite particles size and distribution and the grain boundaries structure, due to the grain boundary energy interaction.

The upper bainite structure is based on the rail morphology [6] of thin ferrite plates (less than 1 μm [7, 8]) and carbide plates located along the rail boundaries. The bainite structure usually consists of certain substructures [9] - packages and blocks. The lower bainite structure also consists of a package of rails, but carbides due to diffusion processes inhibition for most alloying elements, except carbon, are located within the rails. A bundle is a region containing ferrite plates with almost the same direction of crystallographic orientation that are close to each other.

At the same time, the acicular formation of the α-phase (bainite ferrite) is coherently connected with the original austenite crystal lattices. Thus, for the upper temperature region (350-500 ℃) of the intermediate region in carbon steel, it was found that there is an orientation relationship according to Nishiyama between the acicular ferrite lattices and austenite: the (111) austenite plane is parallel to the (110) ferrite plane and the (112) austenite direction is parallel to the (011) bainite ferrite direction [10]. At the same time, it was experimentally established that the steel transformation in the intermediate transformation temperatures region is non-diffusional in nature. Unlike the martensitic transformation, it is associated with the diffuse movement of carbon, which due to super saturation is transformed into cementite or leads to the residual austenite enrichment. Partially carbon-depleted austenite disintegrates by the shear mechanism with the bainite plates formation and packets.

The block, which can even one grain consist, is a region ferrite plates consisting with a more noticeable crystallographic individual plates disorientation in the range of up to 15° (small-angle boundaries). Block and package boundaries are mostly high-angle boundaries and are considered to inhibit crack movement. When using the electron backscatter diffraction (EBSD) method in metallographic studies, it was proposed the general disorientation angle as a criterion for characterizing the grain boundaries influence on steel properties [11].

Today, among metallurgists, there are different views on what can be considered high-angle grain boundaries (HGBs). Some researchers believe that HGB should be greater than 15° [12, 13], while others believe that only HGB greater than 40° [14] or 45° [15, 16] can significantly affect the strength indicators of steels. In fact, the HGB criterion is too general to reflect the polycrystalline structure crystallographic features.

Despite the fact that most of high-strength, low-alloy steels welds metallographic studies are devoted to the microstructure characteristics study and their influence on the weld metal mechanical properties, the relationship between the structural grains size, their crystallographic orientation and fracture toughness is still far from being understood due to the complex polycrystalline metal structure. The current point of view of some researchers, is that the structural units that determine the metal viscosity are grains with grain boundary disorientation angles greater than 15°, but a large experiments number show that cracks can also pass directly through the HGB (as shown in Figure 1). Thus, the effectiveness of traditional grain size parameter using according to expressions 1-3 has significant limitations concerning ferrite-bainite and bainite-martensitic steels.

To describe the polycrystalline microstructure influence on the metal mechanical properties there was proposed [17] a certain differentiation of the grains type (or packets). "Crystallographic" grains and/or packets (referred to as "crystallographic packets") correspond to grains or neighboring units sets having the same crystallographic orientation. "Morphological" grains and/or packets (referred to as "morphological packets") are defined as parallel units bundles that can be observed under a light or scanning electron microscope after appropriate metallographic preparation. In metallographic studies, the crystallographic package size is determined by EBSD, while the morphological packages are studied by light microscopy after etching in a 3% alcoholic solution of nitric acid in alcohol (nital).

The HGB bainite structures good viscosity of the weld metals is related to the high-angle boundaries high density that these microstructures usually have. These boundaries kinds act as barriers to crack propagation, forcing the crack to change its microscopic propagation plane to accommodate the new local crystallography. Low-angle boundaries are not effective barriers and, therefore, have no effect on the steel's viscosity. Therefore, from the fracture mechanics point of view, it is convenient to use the effective crystallographic package concept, which is defined as a continuous ferrite plates set with a crystallographic disorientation below a certain angle (here 15°).

Since the crystal plane {100} bond strength of bulk-centered cubic metals is lower than the other crystal planes strength, the fracture crack mainly propagates along the {100} crystal plane. As a result, more energy is expended for a crack to cross grain boundaries with adjacent grain {100} cleavage plane angles greater than 35° compared to angles less than 35°. The authors [18] showed that a cleavage block, which consists of grains with a {100} cleavage plane less than 35° between grain boundaries, is an effective grain for chipping failure.

The experiments results, which are shown in Figure 2, show the relevant microstructural unit that controls the spelling crack propagation is the crystallographic packet, since only the bainite packet high-angle boundaries (disorientation >40°) can effectively stop the of brittle micro cracks propagation. The bainite packets disorientation 10° or less does not achieve any appreciable the spelling crack deflection, while disorientation more than 10–15° between the {100} cleavage planes corresponding to two adjacent bainite packets can appreciably deflect brittle crack propagation. In the same way, the microstructural unit that controls the brittle fracture propagation in the acicular ferrite microstructure can be defined as a set of adjacent ferrite plates with a crystallographic disorientation less than 15° [19]. The bainite packet is the microstructural unit that controls the low-alloy steels brittle fracture welds metal resistance, and the critical fracture process stage is the brittle crack propagation from one packet to another.

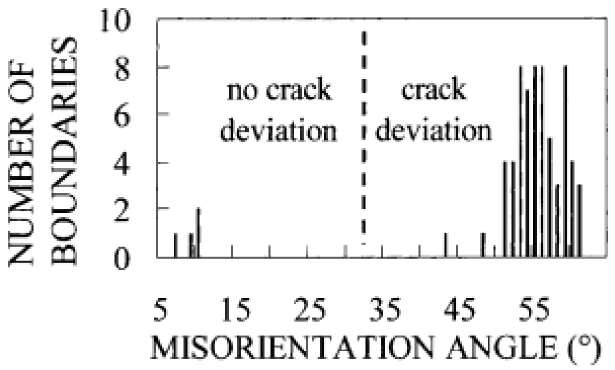

Figure 2. *Histogram of disorientation angle distribution, i.e. that the block size corresponded between neighboring cracked grains in cracked to the lath size. However, the high number of crystals areas: effect of disorientation angle on crack analyzed by EBSD in the present study provides good propagation and deviation [17].*

At the same time, it should be noted that the conditions for the cracks initiation and propagation in the low-alloy steels structure, in addition to the bainite grains crystallographic orientation, are also influenced by such factors as the ferrite bars width, the carbides distribution density, the non-metallic inclusions presence at the crack top, and a number of other microstructural parameters.

3. Conclusion

The conducted studies showed that the relationship between the high-strength, low-alloy steels welds structure and mechanical properties should be described not through the morphological grains size, but through the crystallographic grains or packets size.

To prevent brittle fracture, the orientation angle of crystallographic bainite grains should be less than 15...30^0, which can be ensured by significant structure fragmentation due to the deformation development or thermal deformation processes during welds cooling, the microstructure grinding by adding refractory particles of the appropriate size or selecting a microalloying system.

Abbreviations

IMF	Institute of Metal Physic
IEW	Institute of Electric Welding
EBSD	Electron Backscatter Diffraction Method
HGBs	High-Angle Grain Boundaries

Conflicts of Interest

The authors declare no conflicts of interest.

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