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The relationship between low-temperature toughness and secondary crack in low-carbon bainitic weld metals

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ABSTRACT

This paper aims to reveal the relationship among low-temperature toughness, microstructure and secondary crack from both microstructural and crystallographic perspectives. Instrumented Charpy tests were carried out in the upper platform, transition temperature range, as well as at lower temperatures. Quantitative fractographic analysis, microstructural characterization and secondary crack observation were conducted on half of the impact specimen. Crystallographic features were identified in the secondary crack proximity, e.g. variant selection, orientation relationship, cleavage plane of the corresponding crack matrix. Some results in literature are confirmed. Nickel addition is beneficial to hindering crack propagation as a result of microstructure improvement. The most effective barrier for crack propagation is high-angle misorientation boundaries between Bain packets and the boundaries of ferrite matrix with the microstructure of granular bainite. Additionally, high-angle misorientation boundaries between closed-packed plane packets arrest cracks in the mixed microstructure of fine lath bainite and intricate acicular ferrite. Most preferred crack propagation planes are {110} and {100} in our low carbon bainitic weld metals, with the decreasing possibility of {112} and {123}.

1. Introduction

Welding, as one of the essential technologies, has been widely utilized in industrial applications, e.g. shipbuilding and pipelines manufacturing [1]. Strength and toughness are two key indexes to evaluate mechanical properties of weld metals [2]. Unfortunately, there exists a long-standing dilemma of strength-toughness trade-off in materials science [3]. One efficient method to improve both properties is to add alloy elements, e.g. Mn [4], Si [5], Cr [6], Mo [7], Ni [8,9]. Specifically, strengthening is easily achieved while it is hard to realize toughness enhancement at low temperature. Hence, it is of significant necessity to reveal the crucial aspects that affect the toughness of weld metals.

Ductile brittle transition temperature (DBTT) curve is a functional indication of the toughness variation of steels. The curve can be divided into three regions: the upper platform with ductile fracture, the ductile-brittle transition region with quasi-cleavage fracture and the lower platform with cleavage fracture. The impact energy in these different regions is influenced by various key factors. [10]. For example, Maiti. et al. demonstrate that the inclusion parameters markedly affect the elastic-plastic fracture toughness properties of the X-70 pipeline steels, particularly in the upper shelf and transition temperature region temperature region where failure occurs by ductile and quasi-cleavage fracture, respectively [11]. Lee et al. put forward two useful methods to improve fracture toughness in the ductile–brittle transition region of an SA 508 steel, that is, reducing the total number of carbides, especially the number of M_3C carbides larger than a critical size, and regularly distributing fine M_2C carbides [12,13]. The micromechanisms of cleavage fracture in the lower platform can be characterized by the morphology of cleavage cracks which are retained closely below the fracture surface [14]. Cleavage process is usually composed of the following three steps: microcrack nucleation, microcrack propagation along the particle-matrix boundary, and propagation across the matrix transcending the high-angle boundaries. In terms of the high-angle boundaries, researchers hold various views. In particular, the cleavage facet

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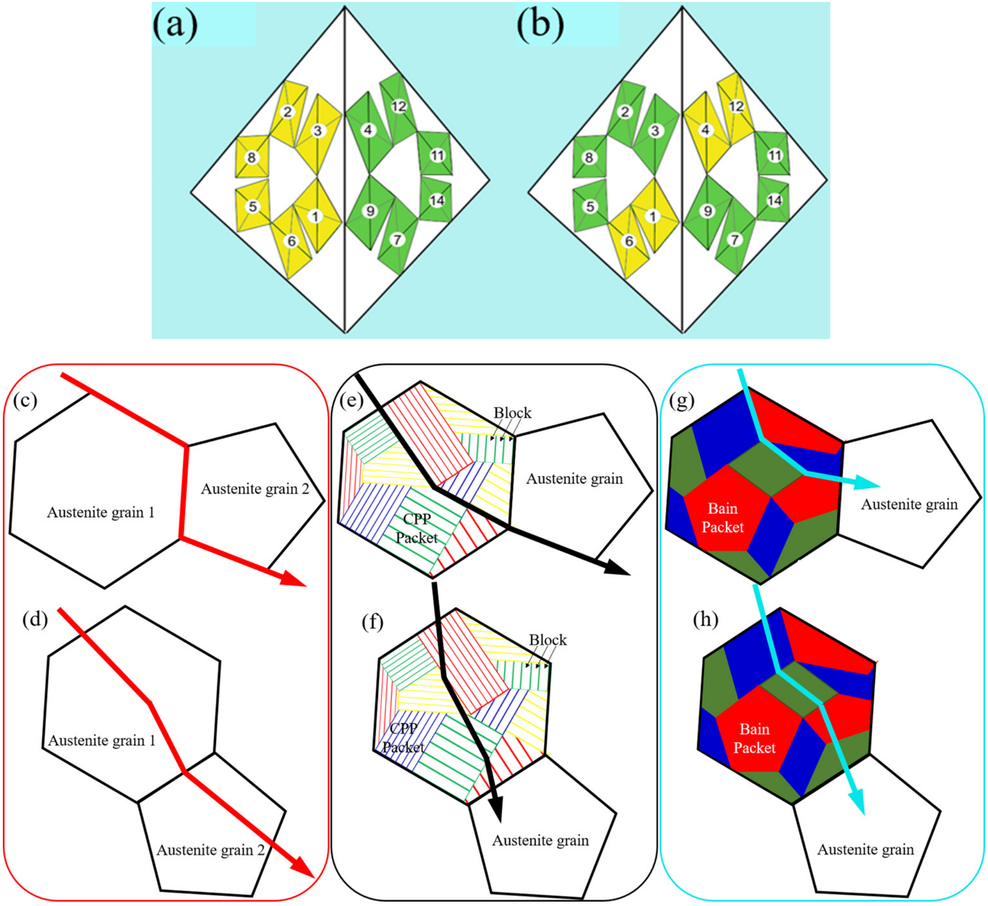

Fig. 1. Two crystallographic packets of KS variants represented in 3D and marked in yellow: (a) a CPP packet and (b) a Bain packet [22]. Illustration of possible crack propagation paths: (c) inter PAG, (d) intra PAG, (e) inter CPP, (f) intra CPP, (g) inter Bain, and (h) intra Bain. Four colors in (c) represent the four CPP packets in one PAG. Three colors in (d) indicate the three Bain packets in one PAG. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

size surmounted by the propagation of matrix is considered as the ferrite grain size in low carbon steels in the vast majority of ferrite microstructures [15]. The plate size is regarded as the matrix barrier in acicular ferrite steels [16]. Deke et al. report that the lath width or the effective plate width controls cleavage fracture in high carbon steels [17]. In low carbon bainitic steels, the packet boundaries act as the obstacle of microcracks. [18]. Brozzo et al. hold the view that the structural unit controlling cleavage fracture can be identified as the covariant bainitic packet because the size of packet is very close to the average unit crack path measured on fractured specimens [19].

Electron backscatter diffraction (EBSD) technique is widely performed on materials structure in the secondary crack proximity to analyze the mechanisms of both crack propagation and crack arrest from crystallographic perspective. For instance, secondary cleavage crack propagation planes are identified to be {100}, {110}, {112} and {123} [20,21]. Herein, some terminologies are introduced to describe the substructure in prior austenite grain (PAG). A rigorous definition of Bain packets and closed-packed plane (CPP) packets was given by previous literature [22], as shown in Fig. 1(a) and (b). Bain packets are assembly of variants connected by low misorientations [23], while in one CPP packet the series of 6 variants share a common $(111)_\gamma$ $//(110)_\alpha$ plane that is close to the habit plane in low carbon steels [24]. A block is the region composed of laths with almost identical crystallographic orientation; the block are rotated along $[110]_\alpha$ axis for 60° in a packet [25]. The substructure boundaries between the blocks are mostly high misoriented to impede cleavage fractures. [19,27,28]. Terasaki et al. state that boundaries between Bain packets can globally change the crack path while local crack path deviation is attributed to the martensite-austenite (M-A) constituents in one Bain packet in bainitic steel [26]. A new software, ARPGE [27], is adopted by Chabok et al. to demonstrate that a large fraction of high-angle grain boundaries arrest crack propagation in a fine structure made of Bain packets [28]. However, little attention is paid on the morphological and crystallographic features of microstructures around secondary crack in low-carbon bainitic weld metals. Based on aforementioned research, two supposing possible paths of crack propagation can be schematically illustrated in Fig. 1(c–h) and safely expressed as follows: (1) inter PAG [15], (2) intra PAG, [15] (3) inter CPP [16–18], (4) intra CPP [19], (5) inter Bain [26], and (6) intra Bain [28].

The goal of this paper is to reveal the relationship among low-temperature toughness, secondary crack and microstructure from the viewpoint of crystallographic features in low-carbon bainitic weld metals, in order to elucidate the most effective boundary to hinder crack propagation in cleavage fracture.

2. Experiment

2.1. Specimen Preparation

Q345 steel plate (450 mm × 250 mm × 28 mm) was employed as the base metal in this study, three metal power flux-cored wires with the diameter of 1.6 mm with added Ni from 0%, 2 wt%, and 4 wt% were utilized as filler metals. The multi-pass bead was deposited using a gas metal arc welding process with a heat input of approximately 1.6 kJ/mm. The inter-pass temperature was controlled at 100 °C and the shielded gas of 95%Ar +5%CO2 was selected. The chemical compositions of weld metals are shown in Table 1.The specimen free of Ni is marked as Ni0, the specimen containing 2 and 4 wt% Ni are marked as Ni2 and as Ni4, respectively.

The Charpy V specimens were machined from the Y-type joint by multi-pass welding through an electrical discharge cutting machine (Fig. 2(a)). The specimens were prepared according to Chinese standard