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Hot cracking behavior of carbide-free bainitic weld metals

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ABSTRACT

In this work, hot cracking behavior of a carbide-free bainitic weld metal was investigated using Varestraint tests and Gleeble hot ductility tests. The results show that the carbide-free bainitic weld metal is as resistant to hot cracking as many of the standard austenitic stainless steel weld metals. The effects of composition, solidification mode, and impurity content on hot cracking susceptibility of carbide-free bainitic steels are discussed. Some guidelines for optimizing their compositions for superior hot cracking resistance are also presented.

1. Introduction

The present authors have recently demonstrated that carbide-free bainitic (CFB) weld metals can be advantageously utilized in welding of quenched and tempered armor steels for realizing significant gains in weld joint efficiency and ballistic performance without any hydrogen-induced cracking problems [1]. CFB steels typically contain relatively higher carbon, silicon, manganese, chromium, and nickel contents compared to most of the familiar and trusted steel weld metal compositions. Further, they may contain some special alloying elements such as cobalt and aluminum. Because of their rather unusual chemistry, solidification cracking is a potential concern in CFB weld metals [2]. Weld solidification cracking is a complex phenomenon, governed by the metallurgical and thermomechanical processes that occur simultaneously in the mushy zone around the weld pool [3]. According to Kou [4], obstruction of solidification shrinkage and thermal contraction of the semisolid weld metal as well as the surrounding solid base metals induces tensile strain in the semisolid weld metal leading to cracking along the grain boundaries that are not fed with sufficient liquid. Cracking susceptibility is known to be a function of many metallurgical factors such as solidification temperature range, primary solidification phase, amount and distribution of terminal liquid, solute redistribution, dendrite coherence, and solidification grain structure as well as mechanical factors such as thermal contraction, solidification shrinkage, and external restraint [5]. In steels, solidification cracking is generally believed to be a consequence of segregation of impurity and/or alloying elements, leading to the formation of low melting eutectics in the form of continuous inter-granular or inter-dendritic films during the final stages of solidification. These terminal liquid films result in cracking when they fail to accommodate the shrinkage and external tensile stresses acting on the weld.

Another closely related, but different, problem is weld metal heat-affected zone (HAZ) liquation cracking during multi-pass welding. Weld metal HAZ liquation cracking (also referred to as weld metal liquation cracking) is a common problem in many materials. Austenitic stainless steels [6] and nickel-base alloys [7] tend to develop low-melting segregates along the grain boundaries during solidification. In such materials, the weld metal deposited in a pass undergoes incipient melting or liquation of the grain boundaries in the HAZ during the next weld pass. These liquated grains in the HAZ crack because of the tensile stress imposed by the solidifying weld metal. HAZ liquation cracking can occur more easily in weld metals and castings than in standard wrought processed base metals because of their cast, coarse, and segregated microstructure, often with some low-melting eutectics at the grain or dendrite boundaries [5]. CFB weld metals contain a number of alloying elements which can strongly segregate to grain boundaries during solidification. Therefore, weld metal HAZ liquation cracking is a potential concern in CFB weld metals.

At present, no reports are available in open literature on solidification cracking or liquation cracking behavior of carbide-free bainitic weld metals. Detailed understanding in these regards is essential for developing better carbide-free bainitic steel compositions. Therefore, in the current study, hot cracking (fusion zone solidification cracking as well as weld metal HAZ liquation cracking) behavior of a CFB weld metal was investigated using Varestraint tests and Gleeble hot ductility tests to broadly assess its suitability for industrial utilization.

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2. Experimental details

Longitudinal Varestraint tests were conducted on specimens machined from groove welds produced in 6 mm thick plates of an armor-grade quenched and tempered steel (nearly equivalent to AISI 4130). These welds were produced using shielded metal arc welding employing specially developed low-hydrogen basic-coated electrodes using a preheat temperature of 350 °C. After welding, the weld coupons were subjected to post-heating at the same temperature for 6 h to obtain a CFB microstructure in the weld metal. For comparison, tests were also conducted on specimens machined from armor steel welds produced using austenitic stainless steel AWS E307 fillers (without using any preheat). This comparison was considered appropriate because austenitic stainless steel fillers are commonly used at present for welding of armor steels in construction of armored vehicles such as main battle tanks [8]. The chemical compositions of the base and weld metals are listed in Table 1. Fig. 1 shows the Varestraint test specimen. Note that only the weld metal portion of the specimen is remelted during Varestraint testing. Tests were conducted as per AWS B 4.0 on a moving torch Varestraint hot cracking test device (Model LT1100, Materials Applications Inc.) at three strain levels (2, 4, and 6%). At each strain level, five specimens were tested. All the tests were conducted using the same set of welding parameters (current = 90 A, voltage = 12.5 V, travel speed = 2.2 mm/s). After testing, each specimen was examined (after some cleaning and buffing) under a stereomicroscope equipped with a measuring scale at 60× magnification to determine the total crack length (TCL) (sum of the length of all the individual cracks in a given test specimen) and maximum crack length (MCL) (length of the longest crack in a given test specimen). Samples cut from some of these specimens were also examined under an optical microscope after standard metallographic preparation. Elemental mapping studies were also carried out on these samples using a scanning electron microscope (SEM) equipped with Energy Dispersive Spectroscopy (EDS).

Hot ductility tests were conducted on all-weld cylindrical specimens machined from the same welds as those used for Varestraint tests. The test specimen dimensions and the test conditions are given in Table 2. Tests were conducted on a Gleeble 3800 thermo-mechanical simulator (Dyna Systems Inc., USA). Unlike Varestraint testing which attempts to quantify the cracking susceptibility by the degree of cracking, hot ductility testing relates the ductility of the material at elevated temperatures to cracking susceptibility. Detailed information on Gleeble hot ductility testing can be obtained from References [9,10]. It essentially involves the following. Initially, a test is conducted to determine the nil-strength temperature (NST) of the material, which is defined as the temperature on-heating at which the strength of the material drops to essentially zero. In this test, a cylindrical specimen is continuously heated at a certain rate under a constant tensile load of 80 N (just enough to overcome the frictional force of the fixture) until fracture. The temperature at which the specimen fails is noted as the NST. Depending on the test material, the NST can be lower than its nominal solidus temperature. Following this, a series of on-heating tests are conducted to determine the nil-ductility temperature (NDT),

Table 1
Chemical composition of base and weld metals.

Element	Base metal	CFB weld metal	Austenitic weld metal[a]
C	0.3	0.32	0.08
Si	0.7	1.60	0.77
Mn	0.9	1.65	4.92
Ni	0.15	1.15	8.09
Co	–	1.10	0.04
Cr	0.85	1.05	17.5
Mo	0.25	0.27	0.27
S	0.003	0.006	0.004
P	0.010	0.008	0.025

[a] The Ferrite Number (FN) of the austenitic weld metal is 4 (~4 vol.% ferrite).

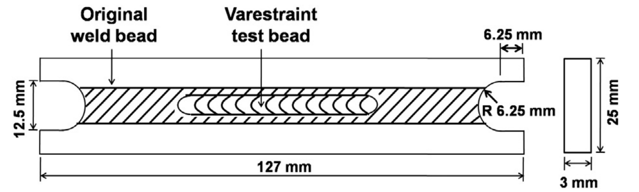

Fig. 1. Varestraint test specimen.

which is defined as the lowest temperature on-heating at which the ductility of the material drops to zero. To begin with, a cylindrical sample is heated at a certain rate to a certain test temperature (typically 100–200 °C lower than the NST temperature) and then it is pulled to failure. The ductility of the specimen is measured in terms of % reduction in area (% RA). Tests are conducted in this manner at successively increasing temperatures until the ductility of the material drops to zero (less than 5% RA). The temperature at which the ductility of the material is zero is noted as the NDT. Following the on-heating tests, a series of on-cooling tests are conducted to determine the ductility-recovery temperature (DRT), which is defined as the highest temperature on-cooling from the NST at which the material exhibits perceptible ductility (more than 5% RA). In these tests, the test specimen is first heated to the NST, cooled to a certain test temperature, and then pulled to failure. The test temperatures are successively lowered and the temperature at which the material exhibits perceptible ductility is noted as the DRT. In the current study, three specimens were tested for determining the NST. On-cooling tests were conducted at the same temperatures as those used for on-heating tests. At each test temperature, both on-heating and on-cooling tests were conducted on at least two specimens. For each specimen, the minimum diameter at the location of fracture was measured using a profile projector and the percentage reduction in area (% RA) was calculated. Longitudinal sections cut from the fractured specimens were prepared for microscopy and microstructures close to the fracture line were examined. Similarly, the fracture surfaces were examined under SEM.

3. Results and discussion

Fig. 2 shows typical solidification cracks in the Varestraint specimens of austenitic and CFB weld metals. In general, cracks appeared radiating from the trailing edge of the weld pool at the instant of straining, as can be seen in Fig. 2a and b. However, in a few CFB weld metal specimens (four out of fifteen), some cracks were found to extend into the weld crater (Fig. 2c). This could be due to some secondary effects and further work is required to understand why crater cracking occurred in CFB welds but not in austenitic welds. In the current study, such crater cracks were not considered in TCL or MCL measurements, as recommended by Lundin et al. [11].

Microstructural examination in the test region of various specimens revealed that the cracks are interdendritic/intergranular, a characteristic feature of solidification cracking (Fig. 3). In CFB weld specimens, EDS elemental mapping studies revealed interdendritic segregation of silicon, manganese, and chromium (Fig. 4). Among the three elements, silicon segregation seemed to be more prominent. Nickel and cobalt, however, did not suffer any noticeable segregation. It is well-known that segregation of alloying elements can promote solidification cracking in steel weld metals. Additionally, in CFB weld metals, it can lead to formation of interdendritic blocky austenite, which is undesirable for the weld metal toughness, as reported by Fang et al. [12]. The results of Varestraint tests are summarized in Fig. 5. In both CFB and austenitic weld metals, the TCL and MCL increased with the applied strain. The cracking data obtained for the austenitic weld metal in the current study is consistent with the findings of earlier investigations for similar compositions [13–15]. Importantly, at any given strain level, the TCL and MCL values for the CFB weld metal are only slightly higher compared to