Fatigue Behavior of Electron Beam Welded Dissimilar Metal Joints

Good fatigue strength properties were achieved joining 4140 steel to 316L stainless steel

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ABSTRACT

The fatigue performance of an electron-beam welded joint between AISI 4140 and AISI 316L steel has been investigated. Results indicated that a good strength weld can be achieved between the two dissimilar steels by electron beam welding with a fatigue limit approaching 190 MPa, which is a value between the fatigue limits of the base materials. The sharper slope in the Wöhler curve of the weld specimen was attributed to the presence of intergranular chromium carbide precipitates within the heat-affected zone.

Introduction

Dissimilar welding of austenitic and ferritic steels is widely used in engineering applications, especially where low-cost combinations of properties such as strength and corrosion resistance are required. Fusion welding methods such as gas metal arc (GMA), flux cored arc (FCA), and gas tungsten arc (GTA) welding have been extensively used for the joining of dissimilar metals since the 1950s (Ref. 1). Depending on the different physical and chemical characteristics of its dissimilar base metals, the weld may also have unique properties. During welding, the weld zone is exposed to high thermal stresses and carbon migration as well as harmful atmospheric effects such as oxide penetration (Ref. 2). These effects may cause catastrophic failures, especially under dynamic loads. To overcome such problems, high power density (on the order of 1 MW/cm^2) welding procedures such as laser beam welding (LBW) and electron beam welding (EBW) have been developed. The low total heat input per length and small weld bead size in these methods result in the minimization of residual stresses and a decrease in brittle phase formation, respectively (Refs. 3–5).

The welding of dissimilar metals provides the means for the flexible design of a component by benefiting from the specific properties of each material to meet the functional requirements (Ref. 6). In the joining of dissimilar metals, having the knowledge of the mechanical and metallurgical properties of the metals is crucial for obtaining a successful weld. In spite of the recurring problems and economic losses that have occurred to date, there still exists a lack of understanding regarding the role of the boundaries and structures in weld-related cracking phenomena. The melting point, coefficient of thermal expansion, and thermal conductivity of the materials must be thoroughly studied, and precautions (such as preheat control) applied as needed (Refs. 7, 8). Consequently, dissimilar metal welding is considered as a much more complex form of welding compared to the joining of similar metals. The most important factor that determines the quality of the dissimilar metal weld is composition. The weld composition will depend on the composition of the base metals, and the composition of the filler metal, if added. The transition zone between the weld interface and the heat-affected zone (HAZ) may contain phases with crystal structures other than the base metals due to the diffusional mixing of alloying and impurity elements, which is why this region may particularly become susceptible to hydrogen and corrosion-related problems (Refs. 9,10). The primary objective of this study was to evaluate the microstructure and fatigue of a ferritic-austenitic dissimilar-metal weld, and to elucidate the possible governing mechanisms by which fatigue occurs in the welded dissimilar steel joint. For this purpose, AISI 4140 steel was welded to an AISI 316L steel by EBW. A rotating beam fatigue testing machine was used for fatigue testing. The characterization of the weld microstructure was done by optical microscopy. X-ray diffraction was used for the identification of the phases within the fusion zone.

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KEYWORDS

Dissimilar Welds
Electron Beam Welding
Fatigue
Stainless Steel
Low-Alloy Steel

Experimental

The materials investigated are 10-mm-thick plates of an AISI 4140 ferritic steel and an AISI 316L austenitic stainless steel. The chemical compositions of these steels, determined by spark emission spectroscopy, are listed in Table 1.

Each of the steels was machined to have the dimensions of 50 mm width and 800 mm length. The specimens were tack welded lengthwise at 200-mm intervals by GTAW to keep the specimens intact prior to EBW. These specimens were then electron beam welded in the butt-joint configuration shown in Fig. 1. Welding was done at at a traveling speed of 8.5 mm s^{-1} without preheating. The welding current and voltage were maintained at 50 kV and 6 mA in a vacuum of 10^{-2} Pa. The distance between the welding gun and the workpiece (i.e., stand-off distance) was held constant at 150 mm. The weldment microstructures of the dissimilar joints were studied by the metallography of various regions using an Olympus optical microscope. A 2% Nital (2 mL HNO_3 and 98 mL methanol) solution was used to etch the ferritic AISI 4140 steel weld and Marble's reagent (4 g $CuSO_4$, 20 mL HCl, and 20 mL water) was used to etch the AISI 316L stainless steel weld. The respective etchants were used to etch the weld interface, the HAZ, and the base metal regions.

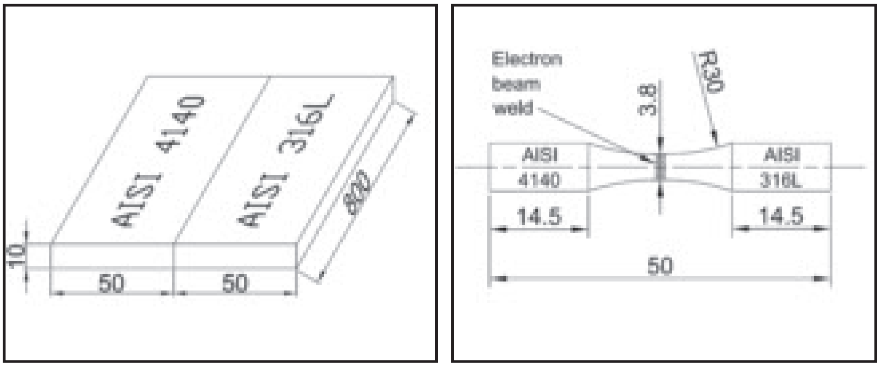

Fig. 1. — A — Configuration of the specimens prior to electron beam welding; B — dimensions of the EBW specimens used for the rotating bending fatigue test. Distances given are in millimeters.

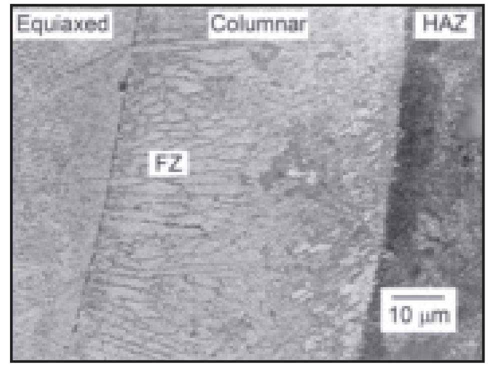

Fig. 2 — Optical micrograph showing the fusion zone and the AISI 4140 side of the weld. The fusion zone (FZ) consists of two regions: equiaxed and columnar. The heat-affected zone (HAZ) of the AISI 4140 side shows dark contrast at the boundary.

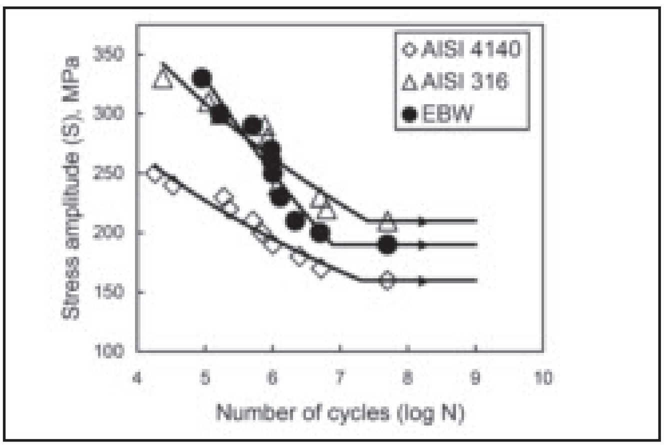

Fig. 3 — The Wöhler (S-N) diagram showing the fatigue test results for the AISI 4140, the AISI 316L, and electron beam welded (EBW) specimen.

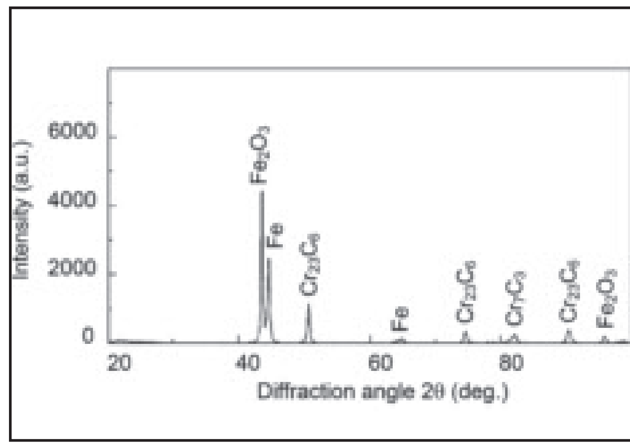

Fig. 4 — The XRD pattern of the weld interface of the electron beam weld.

Structural characterization for phase identification in the fusion zone was carried out on a Rigaku X-ray diffractometer with Cu K $_{\alpha}$ radiation. Fatigue tests were conducted using a rotating beam fatigue testing machine in accord with the ASTM E466 Standard *Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials* at a completely reversed cycle of sinusoidal form (stess ratio $R = -1$) and a frequency of 47 Hz. The dimensions of the fatigue test specimens are given in Fig. 1B. A minimum of nine samples were used for each stress level and the results averaged. The fatigue tests were run out to a maximum of 5×10^7 cycles, at which point they were terminated even if no failure had occurred. The limiting stress at which the material endured the maximum number of cycles was recorded as the fatigue (or endurance) limit.

Results and Discussion

The microstructure of the dissimilar joint is shown in Fig. 2. The weld interface consists of columnar austenite grains followed by equiaxed austenite grains at the center of the weld. The heat-affected zone (HAZ) at the 4140 side of the specimen shows dark contrast. The dark contrast is associated with precipitation of carbides as a result of carbon migration to the AISI 316L steel, which results in the formation of chromium carbides such as $Cr_{23}C_6$ and Cr_7C_3. The 316L side of the weld showed a much smoother transition in terms of microstructure.

The Wöhler diagram for the specimens tested is given in Fig. 3. The curve of the EBW specimen shows a sharper decline with increasing number of cycles. In the low-cycle fatigue region ($N<10^5$ cycles), the EBW specimen outperforms both of the base metals. In the high-cycle fatigue region, the EBW specimen gives average results with values lying between those of the AISI 4140 and the AISI 316L alloys. All of the specimens that were tested exhibited fatigue limits. The fatigue limits of the specimens were recorded as 160 MPa for the AISI 4140 steel, 220 MPa for the AISI 316L steel, and 190 MPa for the EBW specimen. It should be noted that the values plotted in Fig. 3 are average values and that fatigue tests exhibit considerable scatter.

Failure in the dissimilar joints was observed at the HAZ between the weld interface and the AISI 4140 side of the weld. The XRD pattern of the surface of the weld is given in Fig. 4. The XRD pattern belongs to a specimen taken from the fusion zone; however, it should be noted that due to the size of the weld, it is difficult to investigate discrete zones, and the XRD pattern may include results from the HAZ as well. The

Table 1 — Chemical Composition of the Base Metals Used for Electron Beam Welding

Alloy	Composition (wt-%)								
	C	Si	Mn	Cr	Ni	Mo	P	S	Fe
AISI 316L	0.044	0.436	1.376	17.21	10.43	1.638	0.041	0.01	Bal.
AISI 4140	0.394	0.270	0.780	0.901	0.034	0.188	0.017	0.01	Bal.

presence of Fe_2O_3 indicates that oxidation of the surface occurred to some extent. Chromium carbides consisting mainly of $Cr_{23}C_6$ are also present. Chromium carbide particles precipitate preferentially at the grain boundaries and can significantly impair tensile properties (Refs. 11–13). Results therefore suggest that the rapid decrease in the fatigue curve for the EBW specimen is primarily caused by the precipitation of chromium carbides due to carbon migration from the AISI 4140 steel.

Other than the observed rapid decrease in the Wöhler curve, the EBW specimen displayed results comparable to its base metals. Although studies on the corrosion and high-temperature behavior remain to be studied, the current study shows that EBW is suitable for the joining of ferritic and austenitic steels.

Conclusions

The fatigue behavior of an electron-beam welded joint formed between an AISI 4140 and AISI 316L steel has been investigated. The microstructure of the electron-beam welded dissimilar AISI 4140–AISI 316L joint consisted of both columnar and equiaxed austenite grains in the weld interface. An X-ray diffraction pattern of the weld revealed the presence of chromium carbides formed in the weld as a result of carbon migration from the AISI 4140 steel. Fatigue failure occurred at the heat-affected zone (HAZ) between the weld interface and the AISI 4140 side of the weld. The Wöhler curve of the weld specimen displayed a sharper slope compared to its base metals, due to the presence of chromium carbides at the HAZ. The fatigue limit of the weld was comparable to its base metals.

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