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Tribological behavior of electron beam D6ac weldment

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ABSTRACT

A flow formed D6ac steel tubing was joined using electron beam (EB) welding. Thereafter, the EB weldments were treated by tempering at temperatures of 450 °C and 550 °C. After tempering, the microstructural features, mechanical properties, and tribological characteristics of the EB D6ac weldment were studied. This study used a scratch test to evaluate the sliding wear resistance of the tempered weldment. Results indicate that the tempering softens the microstructure by reducing the dislocation density of the flow formed D6ac steel. For the 450 °C/2 h/air cooling tempering treated D6ac steel, the fracture toughness of the EB weldment can be significantly improved. The tribological behavior of the tempered D6ac weldment depended on the tempered microstructures.

1. Introduction

According to the SAE AMS 6431M standard, D6ac is a medium-carbon, low-alloy steel with a high hardenability that is primarily used in ultrahigh-strength structural applications. This type of steel provides a high yield strength/ultimate tensile strength (YS/UTS) ratio. However, the use of these steels is limited by their poor ductility at the highest mechanical strength levels [1]. These steels are produced using a consumable electrode vacuum arc melting process that offers optimum cleanliness and preferable ingot structures, providing optimum transverse mechanical properties.

This study uses two manufacturing processes: flow forming and EB welding. A flow forming process, also known as tube spinning or shear forming, is an advanced chipless metal forming process that is used to manufacture dimensionally precise, round, and seamless hollow components. In this process, the wall thickness is reduced as material is encouraged to flow mainly in the axial direction, increasing the length of workpiece. Flow forming is a cold working rotary-point extrusion technique for forming products with enhanced mechanical properties [2,3]. The flow forming process can form pre-hardened workpieces, thereby eliminating the difficulties and high costs associated with machining, grinding, and honing a hardened and distorted hollow component. The flow forming technique saves raw material, achieves rapid processing, and is cost competitive [4,5]. The flow forming process can be classified into two types of operations: forward and backward flow forming (Fig. 1).

The EB welding is a fusion welding process that produces a weld by impinging a beam of high-velocity, high-kinetic energy electrons to heat and melt the workpiece. Electrons are elementary atomic particles that are negatively charged and have extremely small masses. Raising electrons to a high energy state by accelerating them to approximately 30–70% of the speed of light creates sufficient energy to melt workpieces. The EB welding process is often performed in vacuum conditions to prevent the dissipation of the electron beam. In a vacuum, it is easy to accelerate free electrons and to control their orbits using electric and magnetic fields. Compared to other fusion welding processes, the EB welding offers the advantage of low heat input to the workpiece, resulting in the low distortion and low residual stress of the weldment [6]. The EB welding is becoming more common in the nuclear, chemical, and aerospace industries because of its high depth-to-width ratio and narrow heat-affected zone [7,8].

A post-weld heat treatment (PWHT) process is required to improve the mechanical properties of the weldment. The PWHT process can include many types of treatments. However, the two most common procedures used in steel fabrication are post heating and stress relieving. The PWHT process can improve the

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Table 1
Chemical composition (in wt.%, balance Fe) of D6ac steel.

Element	C	Mn	P	S	Si	Cr	Mo	Ni	V
Specification AMS 6431M	0.42–0.48	0.60–0.90	0.01	0.01	0.15–0.30	0.90–1.20	0.90–1.10	0.40–0.70	0.08–0.15
Used in the present work	0.47–0.48	0.76–0.84	0.01	0.01	0.27	0.98–0.99	1.02–1.10	0.55	0.10

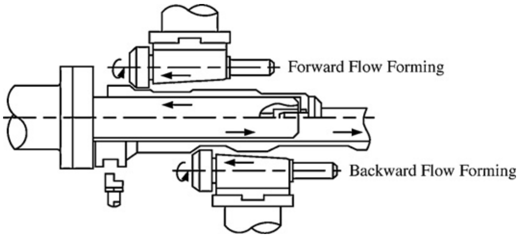

Fig. 1. Principle of flow forming processes.

performance of the weldments by adjusting the microstructure of weld metal. Extant literature offers limited data on the PWHT process for EB D6ac weldments. This information is critical to improving fracture toughness of the tempered weldment. Moreover, Wei et al. [9] examined the effect of tempering conditions on wear resistance of H13 steel. They concluded that the tempering conditions presented different influences on the wear resistance of steel in various wear mechanisms.

The scratch test is a new test method for evaluating the fracture toughness of materials. The scratch test consists of driving a probe, at a certain depth, through a material and is most likely the oldest mechanics-of-materials test for the mechanical characterization of materials. To study the fracture toughness of the tempered weldment, this study assessed the tribological behavior by determining the sliding wear resistance [10]. A flow formed D6ac steel tubing was welded using EB welding and subsequently tempering treated. This study used a scratch test to evaluate the sliding wear resistance of the tempered EB weldment. In addition, the scratch coefficient was used to characterize the wear resistance of the weldment.

2. Experimental details

The experiments in this study used D6ac steel, as specified by the standard AMS 6512C (double vacuum melted VIM-VAR). Table 1 shows the chemical composition of the experimental steel. The chemical composition of the D6ac steel was determined using energy dispersive X-ray spectrometer (EDS) and carbon and sulfur determination.

Prior to flow forming, the D6ac steel tubing was normalized by 910 °C/105 min/air cooling process parameters and machined to a wall of 6.0 mm thickness. Thereafter, it was further reduced to a wall of 2.1 mm thickness using forward flow forming. For the precision flow forming operations, the forward flow forming of the D6ac steel tubing was performed in a three-roller spinning machine (the three rollers were positioned in a 120° design with a spindle speed of 60 rpm and a feed rate of 0.7 mm rev^{-1}). Following flow forming, the tube received a solution treatment of 900 °C/30 min/air cooling.

Thereafter, a flow formed D6ac steel tube was EB welded in a vacuum chamber at a pressure of 1.33×10^{-2} Pa. Table 2 shows the EBW process parameters. The welding process used a heat input of 66.5 J mm^{-1}. To investigate their mechanical properties, the EB D6ac weldments were tempered at temperatures of 450 °C and 550 °C for 2 h, followed by air cooling.

Table 2
Process parameters of EB welding.

Accelerating voltage, kV	120
Beam current, mA	200
Vacuum level, Pa	1.33×10^{-2}
Focal length, mm	444.5
Speed, mm min^{-1}	2100
Pass number	1

A tensile test was used to determine the mechanical properties of the tempered EB weldments. Standard tensile specimens were constructed from the longitudinal direction of the tube and were milled to final dimensions that followed ASTM E370 specifications (Fig. 2). The gauge length of each specimen was 50.8 mm. The tensile test involved two strain rates: 0.2 (mm mm^{-1}) min^{-1}, which was used prior to the yield point, and 2 (mm mm^{-1}) min^{-1}, which was used after the yield point. In this experiment, three specimens were used for each test condition. The fracture surfaces of the tensile specimens were studied using a scanning electron microscopy (SEM).

The microstructural characterizations of the tempered EB weldments were examined using optical microscopy (OM), SEM, and transmission electron microscopy (TEM). All of the metallographic samples were prepared using standard procedures, including mounting, grinding, and polishing them to a 0.05 μm finish, followed by etching with natal (3% HNO_3 solution in alcohol). The tribological properties of the weldments were determined by the scratch test performed using an atomic force microscopy (AFM) in conjunction with the nanoindentation measurement system, which was operated at a constant scan speed of 2 μm s^{-1}. To determine scratch coefficients of the samples that were initiated in low ramp-force mode sliding cycles, the samples were subjected to ramped loads of 500 μN. Using this approach, the corresponding surface profiles were obtained, and 10 μm long scratches were formed using the constant force mode. The rough tip with a radius of 2 mm was applied to the samples at room temperature to avoid an impact cracking event. An X-ray diffractometer (XRD) with a Cu-Kα radiation source ($\lambda = 0.15418$ nm) was utilized to identify the crystalline of the phases present in weld metal.

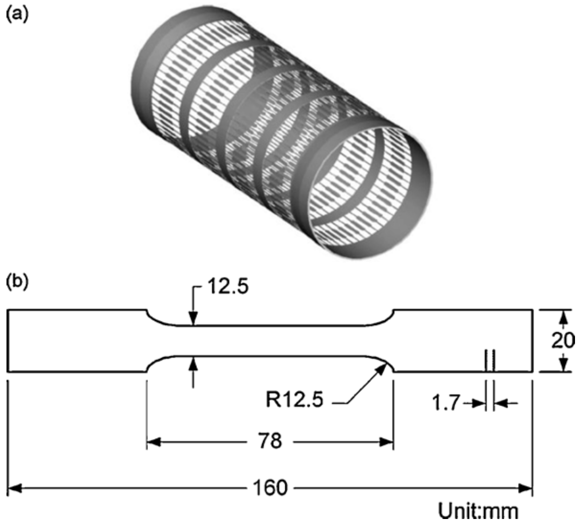

Fig. 2. Tensile specimen of EB welded tube. (a) Layout for procurement of tensile specimens and (b) dimensions of tensile specimen prepared in compliance with ASTM E370.