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EFFECT OF POST-HEAT TREATMENT ON THE IMPACT TOUGHNESS AND CRACK PROPAGATION MECHANISM OF AISI D2 TOOL STEEL MANUFACTURED BY DIRECT ENERGY DEPOSITION

This study investigated the effect of heat treatment on the microstructure and impact toughness property of AISI D2 manufactured with direct energy deposition (DED) and compared the results with conventional wrought material. The fracture crack propagation behavior was examined in connection with microstructures through fracture surface analysis. AISI D2 manufactured with DED had a eutectic structure that turned into a net-type carbide after heat treatment, and Cr-rich needle-type secondary carbide was observed. Impact toughness of DED AISI D2 measured 2.0 J/cm^2 in the as-built sample and 1.1 J/cm^2 in the heat-treated sample. Compared to a wrought heat-treated AISI D2, DED AISI D2 had relatively low impact toughness. DED AISI D2 and wrought material had different crack propagation mechanisms. In DED AISI D2, the eutectic structure and net-type carbide boundary were identified as the major microstructural factor decreasing impact toughness.

Keywords: AISI D2 tool steel; Direct Energy deposition; Post-heat treatment; Impact toughness; Fractograpy

1. Introduction

AISI D2 is a well-known high-carbon, high-chromium-based cold tool steel commonly used in mold and tool industries. AISI D2 is characterized by its high hardenability and outstanding wear resistance, making it ideal for materials in abrasive blades, punches and trimming die applications. In addition, the high carbon content and other additive alloy elements help form an effective carbide reinforcement phase. Carbides have a wide range of distributions and shapes, and this acts as a major factor that influences the microstructural and mechanical properties of AISI D2 [1].

Additive manufacturing (AM) is a process that continuously deposits initial feedstock, such as powders, to manufacture complex 3-dimensional shapes. Recently, many studies have been conducted to manufacture and examine various metals and alloys using AM. Direct energy deposition (DED) is one of the well-known AM methods, and it laminates molten powder using a laser energy source. Since it involves rapid melting and solidifying materials, it forms strong bonding among powders. It can also deposit different materials, allowing partial repair of damaged parts [2]. Steel is one of the most common materials used in DED-related studies. In particular, tool steel is exposed to damages caused by such as partial damage due to the work environment and collisions with components. The component repair process is considered a critical task to reconstruct these damages. The DED additive manufacturing process can significantly benefit when considering a component repair. Meanwhile, when considering AISI D2 tool steel as a structural material, impact toughness is one of the important mechanical properties. However, there has been no study reporting the impact toughness of AISI D2 manufactured with DED. High-carbon steels, such as AISI D2, are vulnerable to cracking during additive manufacturing, making it difficult to build bulk shapes.

This study manufactured bulk AISI D2 using DED and examined the effect of post-heat treatment on its microstructure and impact toughness property. In addition, fracture surface observation was conducted to identify the fracture mechanism of DED AISI D2 in connection with its microstructure.

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2. Experimental

The powder feedstock used was prepared by Chang Sung Co. (Korea) using gas atomization. The prepared powder had a spherical shape and an average powder particle size of 85 μm. Direct energy deposition (DED) was applied using MDG-300 (Maxrotec, Korea), and the process conditions consisted of an areal energy density of 23.81 J/mm^2 and powder feed of 4 g/min. In the case of laser scanning, a zig-zag scanning pattern with a 90° rotation angle was used to obtain high built density and to reduce residual stress. AISI D2 was manufactured on an STS3 build plate, and to minimize thermal cracking during manufacturing, preheating was applied to the build plate at a temperature of 360°C. The temperature was maintained for 2 hours to prevent crack in the sample due to rapid cooling. The manufactured AISI D2 sample was a bulk bar type with 107 mm × 13 mm × 8 mm. To examine the effect of post-heat treatment on DED AISI D2 tool steel, austenitizing and tempering were applied. Austenitizing was maintained at 850°C for 20 minutes, then increased to 1030°C and maintained for 20 minutes, and oil quenching was performed. Tempering was conducted twice at 500°C, 1 hr condition, and air cooling was applied.

To observe the microstructure of the as-built sample and heat-treated sample, grinding with #400 ~ #4000 SiC paper was performed, and mirror polishing with 1 μm diamond suspension was done. Etching was performed for 60 seconds using a 10% Nital solution. The initial microstructures of the as-built and heat-treated DED AISI D2 materials were examined using field-emission scanning electron microscopy (FE-SEM, SU8010, Hitachi) equipped with energy-dispersive spectroscopy (EDS).

Bar type specimen with a cross-sectional area of 4.83 mm × 4.83 mm, length of 80 mm, V-shaped notch of 0.97 mm, and curvature radius of 0.13 mm was machined to measure the impact toughness of DED AISI D2 samples. The impact toughness test was conducted using sharpy impact tester (S1-1B. SATEC). The test was performed on the as-built and heat-treated samples three times for each condition, and the average value of obtained results was adopted.

3. Results and discussion

Fig. 1 shows the SEM observation results of the initial microstructures of the as-built and heat-treated DED AISI D2 materials. The cross-section of the as-built sample shows the austenite matrix and eutectic structure (Fig. 1a). According to Khatibi et al., AISI D2 tool steel melted with a high energy source will form primary metastable austenite and a eutectic structure consisting of austenite and M_7C_3 carbide due to rapid solidification [3]. Element distribution examined using EDS line scanning identified a high Cr concentration in M_7C_3 carbide areas (Fig. 1b). This led to the assumption that the M_7C_3 carbide is mainly Cr_7C_3. And considering that the intensity of elements V, Mo and Mn increased compared to the matrix, it can be inferred that various elements are included in the carbide. Fig. 1c shows the microstructure of the heat-treated DED AISI D2 material. In the lamellar eutectic structure formed in the as-built, austenite was transformed into martensite, and the morphology of Cr_7C_3 carbide changed to net-type caused by the agglomeration process after post-heat treatment. The difference of matrix with heat-treatment was also detected. Park et al. proposed that applying post-heat treatment to AISI D2 manufactured with DED will cause carbon expansion into the eutectic structure from the austenite matrix, and a martensite matrix will form as a result [4]. Furthermore, needle-type precipitation was identified in the heat-treated material, and EDS line scanning confirmed an increase in C and Cr concentrations. The precipitation was analyzed as Cr-rich secondary carbide.

The impact toughness test results of the as-built and heat-treated DED AISI D2 materials are presented in Fig. 2a. Impact toughness measured 2.0 J/cm^2 in the as-built sample and 1.1 J/cm^2

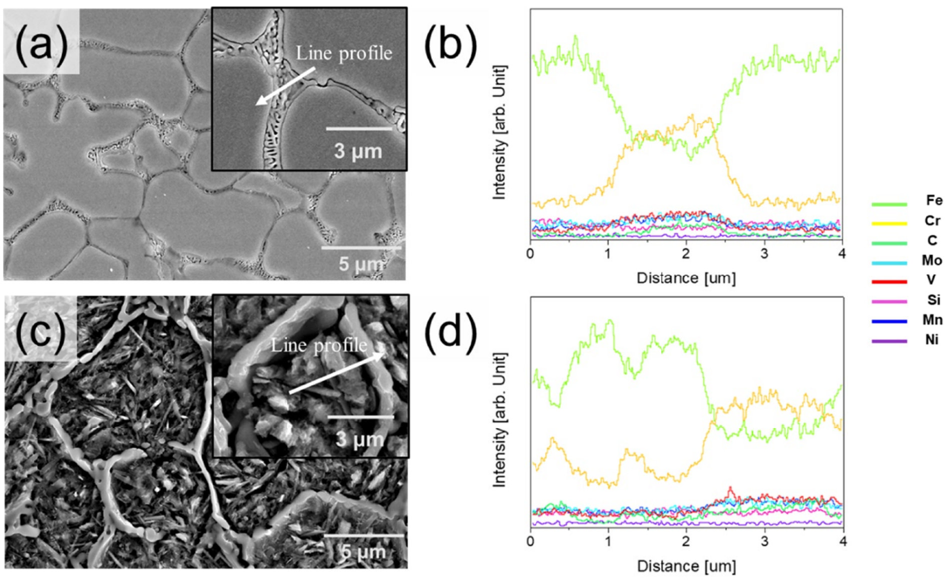

Fig. 1. Microstructure analysis results of DED as-built (a,b) and DED heat-treated (c,d) AISI D2 materials: (a,c) SEM micrographs, and (b,d) EDS line profiling images

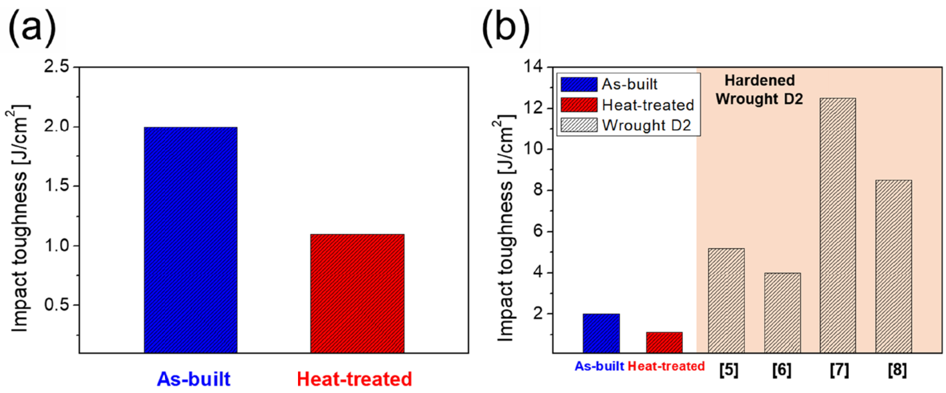

Fig. 2. (a) Impact toughness results of the DED as-built and DED heat-treated AISI D2 steels, and (b) comparison results between DED AISI D2 materials and other conventional wrought AISI D2 materials

in the heat-treated sample, indicating that the heat-treated sample had lower impact toughness property than the as-built sample. Fig. 2b compares the impact toughness values measured for the DED AISI D2 with the values of conventional wrought AISI D2 materials with standard post-heat treatment applied. Conventional wrought heat-treated AISI D2 has an impact toughness value ranging 4~12.5 J/cm^2, indicating that DED AISI D2 has lower impact toughness than the wrought material [5-8].

Fig. 3 shows SEM images of cross-sections of the as-built and heat-treated DED AISI D2 materials after the impact toughness tests. The fracture surface formed along the eutectic structure boundary in the as-built sample, as shown in Fig. 3a. High-magnification observation identified a few damaged eutectic structures, and fine tearing ridges were found along the fracture path area (Fig. 3c). In general, the formation of a tearing ridge is known to increase crack propagation resistance [9,10]. So, to overcome the crack propagation resistance due to formation of tearing ridge, additional energy is required, which is suspected of having contributed to the relatively higher toughness of the as-built material. In the case of the heat-treated DED AISI D2, fractures were formed along the net-type carbide boundary, similarly to the as-built sample (Fig. 3b). High-magnification observation identified fractured net-type carbides and fractures along fine secondary carbides. The fact that carbides are found in the fracture surface indicates that the cracks propagate along the carbide/matrix interface, which is commonly found in other impact toughness test results [11]. In addition, the fine boundaries found throughout the fracture surface are suspected of forming due to the martensite block boundary of the heat-treated sample, martensite. Austenite matrix is more ductile than martensite matrix, requires relatively more energy for crack initiation [12]. The secondary carbide/matrix interface and block boundary in the fracture surface observation above are key factors that reduce crack resistance. The heat-treated sample can be understood to have lower impact toughness than the as-built sample due to these factors that reduce crack resistance.

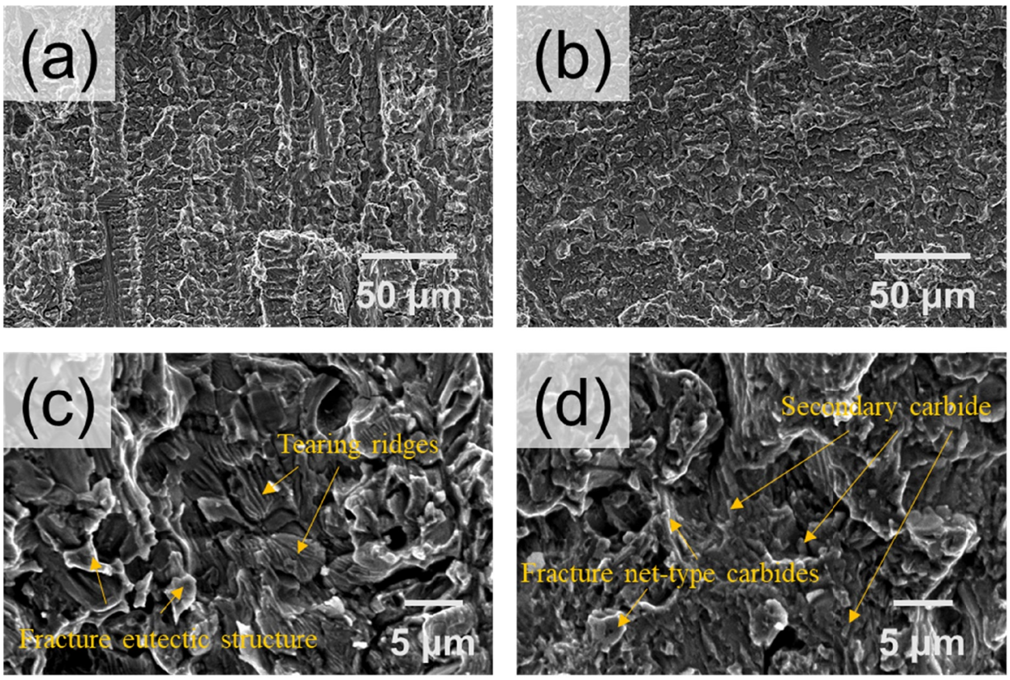

Fig. 3. Observation results for impact toughness fractography: (a, c) DED as-built AISI D2, and (b,d) DED heat-treated AISI D2

Before and after heat treatment, both DED as-built and DED heat-treated AISI D2 materials had relatively lower impact toughness than wrought heat-treated material. This finding can be explained as the difference in microstructural properties and fracture mechanisms. Fig. 4 shows schematic diagrams of the crack propagation mechanisms of the DED as-built, DED heat-treated and wrought heat-treated AISI D2 materials. In the case of the DED as-built and DED heat-treated materials, crack propagation mainly occurs along the eutectic structure and net-type carbide boundary. In this regard, the eutectic structure of connected geometry acts as a vulnerable area in the interface with the matrix, and when stress is applied, it acts as the main crack propagation point reducing the impact absorption energy. Furthermore, in the case of tempered martensite, it is vulnerable to stress concentration, which is reported to decrease toughness performance [13]. Carbides in the wrought heat-treated AISI D2 exist as a block-type shape. The coarse primary carbides in wrought AISI D2 are exist in separate each other and induces stress concentration, which will cause crack formation [6]. The crack initiates in the carbide and propagate to the matrix. The crack formation and propagation along the eutectic structure and net type carbide boundary in the DED sample acts as a major factor that reduces impact toughness more than the wrought heat-treated AISI D2.

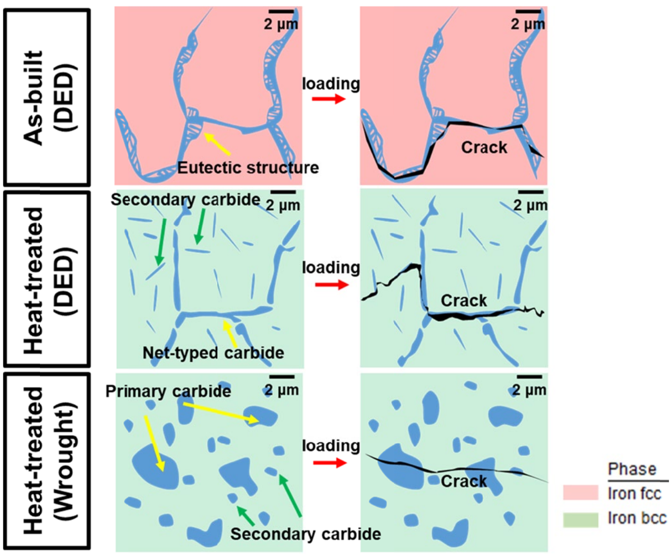

Fig. 4. Schematic diagrams of crack propagation mechanisms of DED as-built, DED heat-treated, and wrought heat-treated AISI D2 steels

4. Conclusions

This study examined the effect of post-heat treatment on the microstructure and impact toughness of bulk AISI D2 cold work tool steel manufactured with the DED process. A eutectic structure consisting of austenite and M_7C_3 carbide was identified in the as-built sample. A eutectic structure that turned into a net-type carbide in the heat-treated sample and needle-type secondary carbide was also identified. The impact toughness of the as-built material measured 2.0 J/cm^2, and the heat-treated material measured 1.1 J/cm^2, indicating that the as-built material had a greater impact toughness property than the heat-treated material. Compared to the conventional wrought heat-treated AISI D2, the DED AISI D2 materials had relatively lower impact toughness values. In common, cracks propagated along the eutectic structure and net-type carbide boundary in the as-built and heat-treated AISI D2 materials. In fracture surface analysis, fine tearing ridges were found in the as-built DED material, and martensite block boundary and secondary carbide were found on the surface of the heat-treated DED material. The eutectic structure and net-type carbide boundary are proposed as a key microstructural factor that decreases the impact toughness of the DED AISI D2 material.

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