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Properties of wire + arc additively manufactured 2024 aluminum alloy with different solution treatment temperature

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Abstract 2024 aluminum alloy deposits were produced with wire + arc additive manufacturing procedure. Solution treatment + natural aging processes with different solution treatment temperature were conducted to improve the properties. The microstructure and mechanical properties were investigated. After heat treatment the distributing characteristic of the second phase changed to be dispersive from continuous in as-deposited condition. Solution treatment + natural aging process can significantly improve the properties of WAAM 2024 aluminum alloy. With higher solution treatment temperature, the micro hardness, tensile properties and elongation presented an increasing trend. After 503°C solution treatment + natural aging process, the micro hardness, ultimate tensile strength, yield strength and elongation were 143HV, 497MPa, 330MPa and 16%, respectively, which can nearly meet the applying requirement.

Keywords *wire + arc additive manufacturing; metals and alloys; solution treatment temperature; microstructure; mechanical property*

1. Introduction

Wire + arc additive manufacturing (WAAM) process is a new technique for directly fabricating components by melting and depositing filler wire layer by layer with arc as the power source [1-3]. AA2024 aluminum alloy, one of the 2000 series high strength aluminum alloys, has been widely applied into aerospace industries, such as airscrew and missile, for its high strength to weight ratio and good mechanical properties [4]. Employing WAAM technique to fabricate high strength aluminum alloy has drawn attention of aerospace industries.

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The formation, microstructure and mechanical properties of WAAM aluminum alloy regulated through controlling the wire [5], arc mode [6], fabricating parameters [7], and other auxiliary measures [8] are the recent research focus. Conventional WAAM technique cannot directly fabricate AA2024 components due to the inexistence of commercial wire with the same compositions of AA2024 aluminum alloy. Qi [9] built a double-wire + arc additive manufacturing system, making it feasible for building Al-Cu-Mg alloys with different element compositions using conventional commercial wires. While, the properties were comparatively lower than the applying requirements. Solution + aging heat treatment has been proved to successfully improve the properties of WAAM Al-6.3Cu components by Gu [10] and Bai [11]. AA2024 aluminum alloy also can be strengthen through heat treatment, and its properties ranged with the solution treatment temperature.

In this paper, WAAM 2024 aluminum alloy thin wall components were produced. Solution treatment with different temperature + natural aging procedures were performed to process the components. The microstructure and mechanical properties of the deposits in different conditions were investigated.

2. Experiments

Two binary aluminum alloy wire, ER2319 (Al-6.3 wt% Cu) and ER5087 (Al-5 wt% Mg), were simultaneously fed to build single-pass and multi-layer thin wall components. The feed speed of ER2319 and ER5087 wire were set to be 2.4 m/min and 1.05 m/min to achieve similar element composition of AA2024 [9]. As the composition of WAAM deposit (Al-4.44Cu-1.49Mg wt%) is similar to that in AA2024 (Al-4.4Cu-1.5Mg wt%), the deposits will be taken as WAAM 2024 aluminum alloy. Other parameters, such as the torch travel speed (300 mm/min), VP-GTAW arc (120 A, 100 Hz, DCEN:DCEP = 4:1), arc length (5 mm) and flow rate (18 L/min) of 99.99% argon, were kept constant for all deposits.

Solution treatment + natural aging (T4) were conducted to process the deposits. The deposits were heated to the solution treatment temperature (485°C, 498°C and 503°C, respectively) holding for 90 min, and followed with water quench, then kept for 48h at room temperature for natural aging. Therefore, the deposits with four conditions (as-deposited, 485°C-T4, 498°C-T4 and 503°C-T4) were obtained.

The center area of the deposits was employed for microstructure and micro hardness test. The area from center to both end were selected to machine to be tensile samples along welding direction. The microstructure was investigated through X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectrometry (EDS). The mechanical properties were characterized with micro hardness and tensile properties.

3. Results and discussion

The XRD results showed that besides the dominant phase α-Al, θ phase (Al_2Cu) and S phase (Al_2CuMg) also existed in the as-deposited component (Fig. 1a). When the molten 2024 aluminum alloy depositing metal solidified, non-isothermal eutectic reaction ($L \rightarrow L + \alpha \rightarrow L + \alpha + \theta \rightarrow \alpha + \theta + S$) occurred with α-Al, θ phase and S phase inside [12]. After solution treatment + natural aging process, α-Al and θ phase still existed in the components, while, S phase cannot be detected (Fig. 1b, Fig. 1c and Fig. 1d).

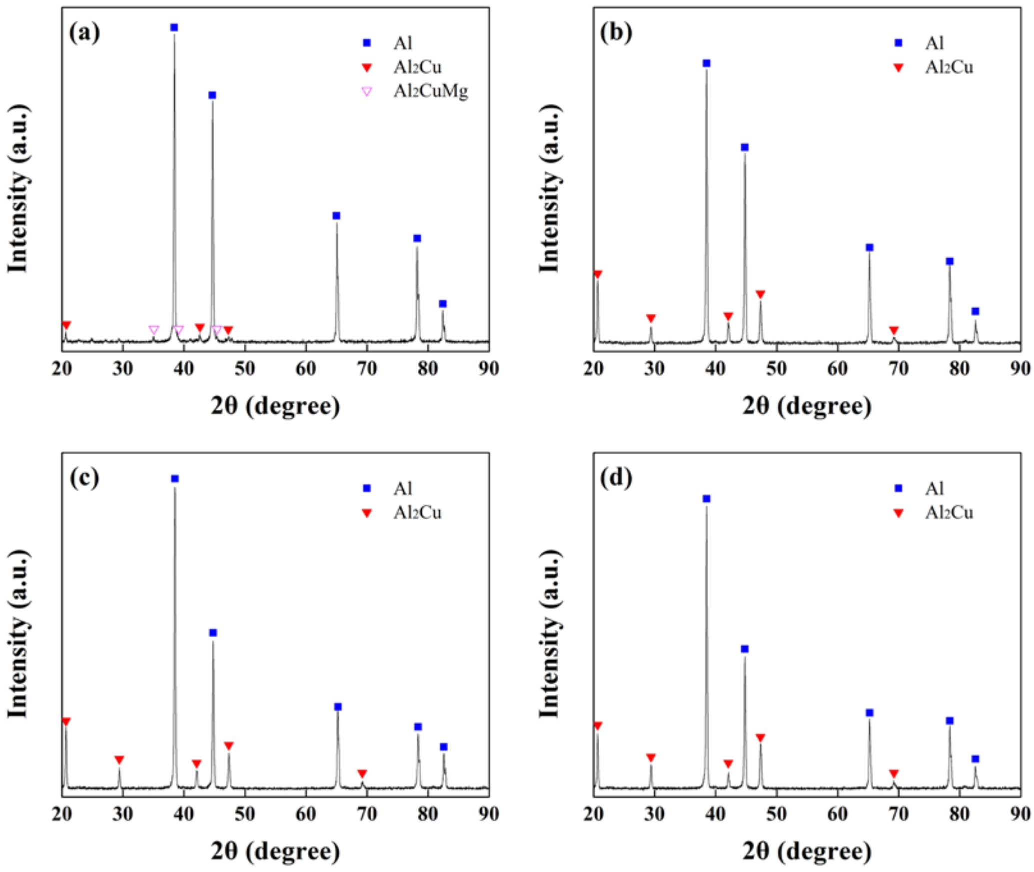

Fig. 1. XRD results of 2024 deposits (a) as-deposited; (b) 485°C-T4; (c) 498°C-T4; (d) 503°C-T4

The SEM images showed the second phase mainly presented continuous distributing characteristic along grain boundary in as-deposited 2024 aluminum alloy, with a small number of phase dispersing in the matrix (Fig. 2a). The detected EDS data indicated the bright white phase was θ phase (Al_2Cu), and the dark white one was S phase (Al_2CuMg), which distributed in the black α-

Al matrix. After T4 heat treatment, the continuous second phase was broken, and dispersed distributing characteristic can be seen. With higher solution treatment temperature, the dispersion distributing effect of the second phase presented an increasing trend (Fig. 2b, Fig. 2c and Fig. 2d). As described by Protasova [13], with higher treatment temperature the contact angle of the solid phase particles increased, and the grain boundaries was regarded as incompletely wetted and appeared interrupted. The second phase was analyzed to be α-Al + θ eutectic phase.

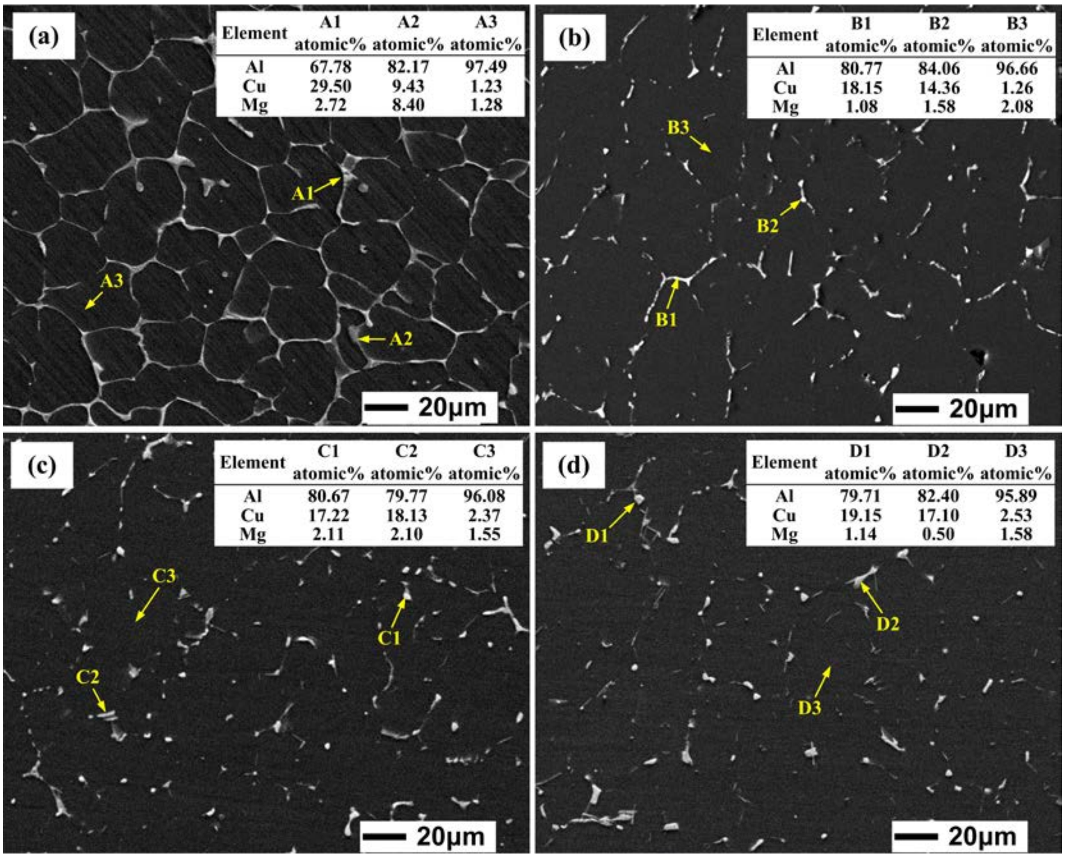

Fig. 2. SEM images of 2024 deposits (a) as-deposited; (b) 485°C-T4; (c) 498°C-T4; (d) 503°C-T4

It can be seen from Fig. 3 that the micro hardness value of as-deposited 2024 alloy ranged from 92HV to 98HV, and the averaged value was 95HV, which only reached 74% level of the hardness value in AA2024-T4 plate (125HV). While, it was 133HV, 138HV and 143HV respectively in 485°C-T4, 498°C-T4 and 503°C-T4 conditions, which has been improved by 40%, 45% and 51% compared with that in as-deposited condition. Although the micro hardness fluctuated among different testing points, each of them exceeded the hardness value of AA2024-T4 plate. The micro hardness of WAAM 2024 aluminum alloy can be remarkably improved by solution treatment + natural aging process, and it increased with higher solution treatment temperature.

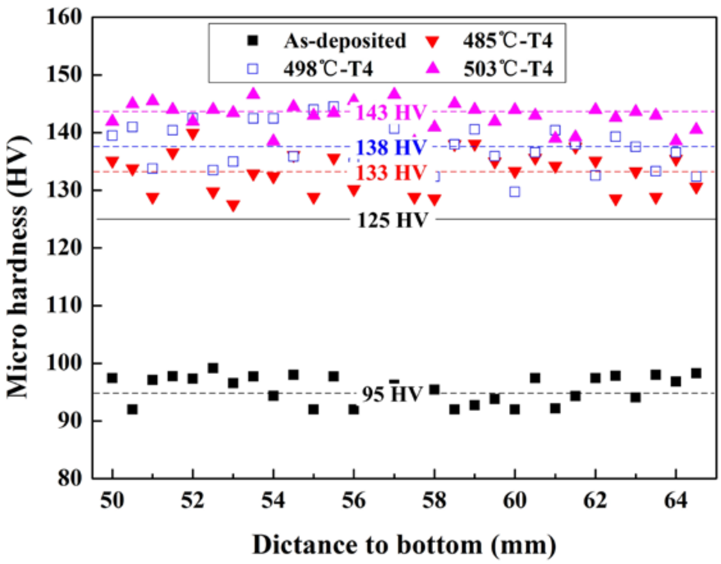

Fig. 3. Micro hardness of 2024 deposits in different conditions

Fig. 4 reveals the ultimate tensile strength (UTS), yield strength (YS) and elongation testing results of the four samples. The UTS, YS and elongation of as-deposited 2024 aluminum alloy was 284MPa, 177MPa and 6%, which were distinctly lower than the properties of AA2024-T4 plate (UTS: 470MPa, YS: 325MPa; Elongation: 20%) and cannot meet the applied requirements. The solution treatment + natural aging process can significantly improve the tensile properties. In addition, the UTS, YS and elongation presented an increasing trend with higher solution treatment temperature. After 503°C solution treatment + natural aging, the UTS, YS and elongation was 497MPa, 330MPa and 16%, respectively. The tensile strength can reach the level of AA2024-T4 plate, while, the elongation was a little lower.

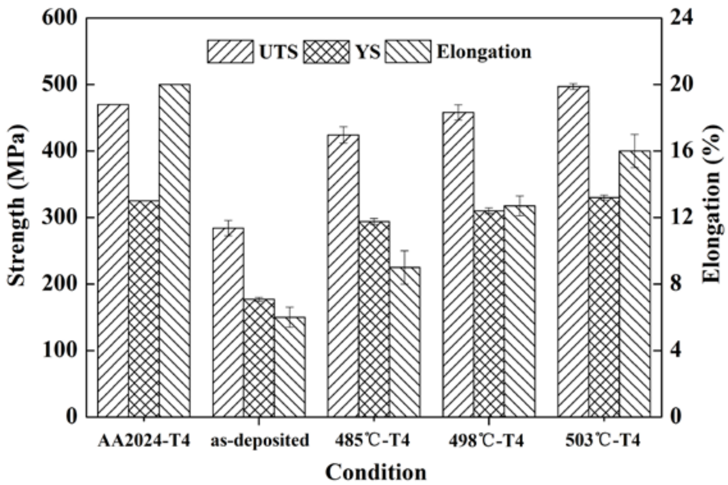

Fig. 4. Tensile properties of 2024 deposits in different conditions

4. Conclusions

In this study, WAAM 2024 aluminum alloys were produced, and solution treatment with different temperature + natural aging procedure were conducted. The microstructure and mechanical properties of the samples were investigated. The conclusions can be drawn as following.

(1) After solution treatment + natural aging, the second phase turned to be α-Al + θ eutectic, and presented dispersed distributing characteristics.

(2) Solution treatment + natural aging procedure can improve the micro hardness, tensile properties and elongation of WAAM 2024 aluminum alloy. The properties presented an increasing trend with higher solution treatment temperature. With 503°C solution treatment temperature, the properties can nearly reach the applying level.

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