

Geometric Limitation and Tensile Properties of Wire and Arc Additive Manufacturing 5A06 Aluminum Alloy Parts

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Wire and arc additive manufacture (WAAM), as an emerging and promising technology of metal additive manufacturing, it lacks of experimental works to clarify the feature of geometrical configuration, microstructure and tensile properties, which can be used for further evaluating whether the as-deposited part can be used directly, and providing design reference for structure optimization. Taking 5A06 aluminum alloy additive manufacturing for example, in this paper, the geometric limitation and tensile property criteria are characterized using experimental method. The minimum angle and curvature radius that can be made by WAAM are 20° and 10 mm when the layer width is 7.2 mm. It shows isotropy when loading in build direction and perpendicular one. When loading in the direction of parallel and perpendicular to texture orientation, the tensile properties are anisotropic. The difference between them is 22 MPa.

Keywords geometric limitation, mechanical anisotropy, microstructure, tensile property, wire and arc additive manufacture

1. Introduction

As an important engineering structure material for aircraft and space vehicles, 5A06 aluminum alloy is widely used as fuselage skin, aerofoil, fuselage frame, fuel tank and so on. To ensure longevous service and the high reliability, large-scale, integrated and functional 5A06 aluminum alloy components are preferable for aeronautical manufacturing. Wire and arc additive manufacture (WAAM) characterized with high efficiency and low cost is thought to be preferable for rapid prototyping large-scale aluminum alloy part. However, it lacks basic data to clarify the geometric limitation of WAAM and performance criteria, which are the reference data to evaluate whether the geometric configuration can be achieved using WAAM and whether the mechanical properties of as-deposited part can meet the requirement of service conditions.

Cranfield University together with Rolls-Royce started to center on developing wire and arc additive manufacture as a means of reducing the wastage levels of expensive and high-performance alloys that can occur in conventional processing, such as nickel-based alloy and titanium-based alloy at the beginning of 1990s (Ref 1). Until a major three and a half year

€2.7 million European research project entitled rapid production of large aerospace components (RAPOLAC) was approved to develop WAAM based on cold wire feed gas tungsten arc welding (GTAW) in Cranfield University, WAAM technology has got more and more attention for its distinct advantages in forming efficiency and cost. Research work about WAAM continues at the University of Nottingham (Ref 2), the University of Wollongong (Ref 3) and Southern Methodist University. Kazanas investigated the production of geometric features using wire and arc additive manufacturing with positional welding. It is also useful for building features with limited accessibility without manipulating the workpiece. Inclined, horizontal wall and enclosed features could be built using an inclined torch (Ref 4). They clarified the forming ability of spatial geometric shape using WAAM. How about the forming ability of plane geometric shape? It determines whether the final part can be deposited with layer-up-layer fashion using WAAM. In AM path planning, a stack of 2D closed contours is obtained when a 3D model is sliced. Each slice may have a set of closed contours or polygons (Ref 5). Many types of tool-path patterns have been developed for AM, such as raster scanning path technique (Ref 6), which is simple implementation and suitability for almost any arbitrary; zigzag tool-path generation (Ref 7), which is the most popular one in commercial AM machine; and spiral tool-path generation (Ref 8), which has been widely used in numerically controlled (NC) machining. They all concentrate on the importance of filling the outline of the image with vector motions. However, WAAM is different from laser additive manufacturing, and because of the large molten pool and surface tension, sharp angle and curve shape with large curvature usually cannot be formed accurately. Ding et al. (Ref 9) provided a method of decomposing 2D geometries into a set of convex polygons basing on a divide and conquer strategy, so as to simplify the complex shape. However, it also encountered the above-mentioned problem. Plane geometric limit is a constrain condition for 2D path planning.

The feature of geometric configuration, microstructure and property of aluminum alloy deposited using WAAM technology is still needed to be further studied, which can be used for

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further evaluating whether the as-deposited aluminum part can be directly put into service. Similar to casting and forging, WAAM should also establish related standard to facilitate the industrial application. Now it lacks industrial standard to evaluate the additive manufactured parts from geometric configuration and mechanical property perspective. What is the minimum limit of geometry, such as the minimum radius of curvature, the minimum angle? The as-deposited Ti-6Al-4V part has distinct microstructure and mechanical anisotropy (Ref 10), which will confine the structure layout comparing the isotropic materials. Then, is the as-deposited 5A06 aluminum alloy anisotropic or isotropic? This paper aims to clarify them and provide basic data about additive manufactured 5A06 aluminum alloy for path planning and structure designer. So plane geometric configuration and tensile properties (ultimate tensile strength and elongation) are characterized.

2. Experimental Procedure

A 1.2-mm 5A06 aluminum alloy wire was used for shape metal deposition process. Chemical composition and mechanical properties of the raw 5A06 alloy acceptance test are shown in Table 1. The wire was supplied by a motorized wire feeder which matched the GTAW welding machine, EWM, Tetric 521 Synergic AC/DC. A four-axis computer numerical control machine was used to execute the preset forming path. Welding gun was vertically fixed onto a traveling cantilever, and wire was feed at an angle of 30° from the substrate surface in side direction. The plates with dimension of $400 \times 200 \times 8$ mm were ground with 400 grit sand paper and then degreased with acetone and ethanol before being used. A water-cooled backing plate was used to help to control the inter-pass temperature at about 80°C .

All experiments were carried out in ambient atmosphere, and the deposition direction was unaltered starting at the same position. Rectangular pulse alternating current power supply mode was adopted to achieve depositing process. The process parameters used in the geometric limitation observation are listed in Table 2. A three-factor and four-level single-factor experiments were designed to illustrate the effect of main parameters, i.e., peak current, travel speed and wire feed speed, on tensile property. The peak current (I_p) was set to 120, 140, 160 and 180 A, the background current (I_b) was set to $I_b = I_p - 50$ A, pulse frequency was 50 Hz, and duty cycle was 0.5. Travel speed (v_T) was 0.15, 0.20, 0.25 and 0.30 m/min. Wire feed speed (v_W) was 1.2, 2.0, 2.8 and 3.6 m/min.

The 5A06 aluminum alloy was deposited layer by layer onto the substrate with a single bead. Ten straight walls were produced with 400 mm long and 100 mm high. Tensile specimens were extracted parallel and perpendicular to the build direction and solidification texture orientation. The tensile specimens had a dog-bone shape with a gauge length of

28.0 mm and a cross-sectional area of 8.0×3.0 mm, as shown in Fig. 1. Three specimens extracted in each direction were tested and averaged to evaluate the tensile property. The specimens were extracted from the walls using the arrangement shown in Fig. 2. The specimens deposited with varying current 120, 140, 160 and 180 A are numbered 1-4. The specimens deposited with varying travel speed 0.15, 0.20, 0.25 and 0.30 m/min are numbered 5-8. The specimens deposited with varying wire feed speed 1.2, 2.0, 2.8 and 3.6 m/min are numbered 9-12. Tensile test was carried out with an Instron 3382 electromechanical machine with a 100-kN load cell. A dynamic strain gauge extensometer with a gauge length of 25 mm was attached to each specimen while testing to measure 3% tensile strain. Samples for the observation of microstructure were cut along the build direction and examined using optical microscope.

3. Results and Discussion

3.1 Geometric Limitation for WAAM Process

Because of the large molten pool and the effect of surface tension, some plane shapes cannot be deposited using WAAM,

Table 2 Deposition parameters

Parameters, unit	Notation	Value
Peak current, A	I_p	160
Base current, A	I_b	110
Average current, A	I_{AV}	122
Peak time, s	T_p	0.1
Base time, s	T_b	0.1
Travel speed, m/min	v_T	0.25
Wire feed speed, m/min	v_W	2.0
Average volt, V	U_{AV}	16.4
Layer height, mm	h_1	1.3

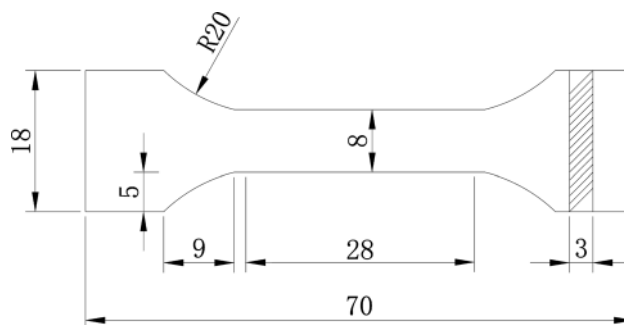


Fig. 1 Schematic drawing of the tensile sample

Table 1 Major chemical composition and mechanical properties of the raw 5A06 wire

	Major chemical composition, wt.%		Mechanical properties	
	Mg	Al	Tensile strength, MPa	Elongation, %
5A06	6.4	93.6	346	12

such as sharp angle and curve shape with large curvature. They play as the geometric limitation for forming path planning and geometric structure designing. Experimental method is used to clarify the geometric limitation for GTAW-based additive manufacture. Figure 3 shows plane shapes with sharp angle of 10° , 15° and 20° . The geometric shape with angle of 20° can be deposited in accordance with the planed path. The angle between the two axes of weld beads is 19° , and the intersect angle of the inner outline is 18° . Both of them are close to the set value. Reducing the angle to 15° , the intersect angle of the two axes of weld beads is equal to the preset one. The intersect angle of the inner outline is only 9° , which is much smaller than the preset value. It needs further machining work to obtain the final geometric shape. When the angle is set to 10° , the triangles' sides within 49.5 mm from the vertex are overlapped owing to surface tension. The intersect angle of the two axes of weld bead is 7° , and the inner outline of the angle is failed to be built. It is difficult to obtain the designed plane shape. So depositing angle exceeding 20° is preferable for WAAM.

Shape distortion causing by surface tension is a main problem to go against depositing small-sized plane shapes. The same problems are encountered when depositing curve with large curvature, and Fig. 4 shows the deposited curve shapes with curvature radius 5, 10 and 20 mm, respectively. In Fig. 4(a), the actual curvature radius is 20.25 mm, which approximates to the designed one. Outlines of as-deposited curve shape are smooth, and they are nearly parallel to the centerline of the geometric shape. When the curvature radius is set to 10 mm, the actual one 9.25 mm of as-deposited shape is slightly smaller than the set value, as shown in Fig. 4(b). Inner outline is distortional due to materials accumulation at the turning position of weld gun. In Fig. 4(c), this phenomenon is more obvious. Although the centerline of the shape is closer to

the designed one, the inner outline is severe distorted. WAAM is not suitable to deposit plane shapes with sharp corner and turn. In addition, the geometric limitation for WAAM is also related to the layer width. In general, the layer is wider, and it is more disadvantageous to deposit plane shapes with sharp corner and turn.

When depositing the plane shape with sharp angle, the shape distortion at the angular point is mainly caused by the molten metal wetting on the previous weld bead. When depositing the shape with curve, the outline distortion is caused by the molten metal accumulation at the sharp turn because of surface tension. Depositing the two above-mentioned plane shapes, weld bead overlapping usually happens at the position of angular point and curve with large curvature. The minimum spacing of the weld bead centerlines decides the geometric limitation in a manner of overlap amount. Figure 5 shows the images of the two-pass weld bead with different centerline spacing.

Increasing the centerline spacing from half of the layer width to nine-tenths of the layer width, the two weld beads are detached gradually. Nine-tenths of the layer width is the minimum centerline spacing to obtain separate weld beads. If the spacing is less than this value, the final obtained shape is determined by the surface tension and the two weld beads are overlapped. So in Fig. 3(c), when the vertical distance increases to 7.5 mm what is nearly equal to the layer width, the initial and terminal sides of the angle begin to separate from each other. In Fig. 4(c), when the curvature radius is set to 5 mm, molten metal accumulates rapidly at the curve segment where the span is equal to nine-tenths of layer width, so inner outline of which is distorted and the designed plane curve shape cannot be deposited accurately. Plane angle of 20° and curvature radius 10 mm are the geometric limitation for WAAM when layer width is 7.2 mm.

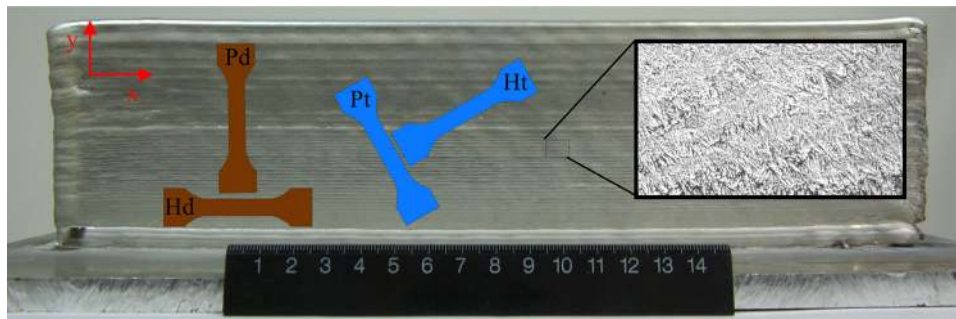


Fig. 2 Schematic diagram showing the extraction of the tensile specimens from the wall. In labeling the specimens, Pd indicates the specimen was machined parallel to y (build) direction, Hd indicates x (perpendicular one), Pt indicates the specimen was machined parallel to the solidification texture orientation, and Ht indicates perpendicular one

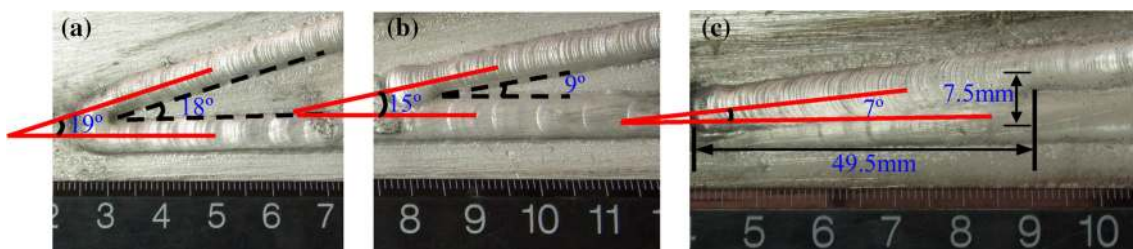


Fig. 3 Plane shapes with sharp angle of (a) 20° , (b) 15° and (c) 10° deposited using WAAM

3.2 Tensile Properties in the Direction of Parallel and Perpendicular to Build Direction

Whether the 5A06 aluminum alloy parts deposited by WAAM are mechanical anisotropic is experimentally observed in this section. Wire and arc additive manufactured Ti-6Al-4 V has large columnar grains which are aligned almost perpendicular to the substrate (Ref 10). Tensile strength and elongation are anisotropic when tested from parallel and perpendicular to build direction. The microstructure of wire and arc additive manufactured 5A06 aluminum alloy part is quite different from the additive manufactured Ti-6Al-4 V. Large columnar grains cannot be observed, instead of which multi-layer structure is formed. Figure 6 shows the microstructure of 5A06 aluminum alloy part manufactured by WAAM.

The periodic microstructure is formed in process of layer-up-layer cladding. Obvious fusion line can be observed in magnified image of bounding region. The different microstructures of bounding region and inner layer perform as multi-layer structure. The tensile specimens that are extracted from the single-wall part in x and y directions are tested to clarify whether the periodic microstructure will result in mechanical anisotropy. Figure 7 shows the stress-strain curve of specimens along x and y directions.

Under axial tensile load, the two specimens perform similar mechanical response. The yield strength is 125 MPa, and the tensile strength is 277 MPa. There is a small difference in elongation. The elongation of specimen in y direction is 2% larger than specimen in x direction (34%). Because cross-sectional microstructure of specimen in y direction is almost

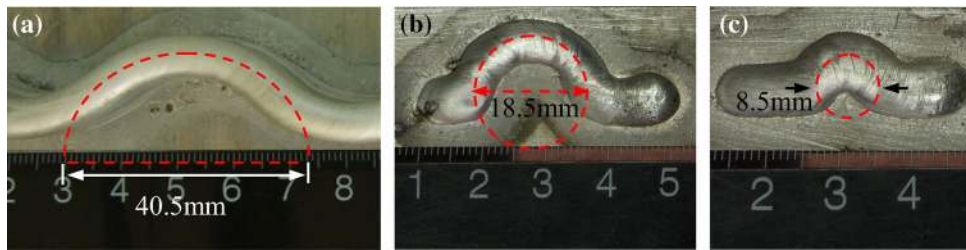


Fig. 4 Curve shapes with curvature radius of (a) 20 mm, (b) 10 mm and (c) 5 mm deposited using WAAM

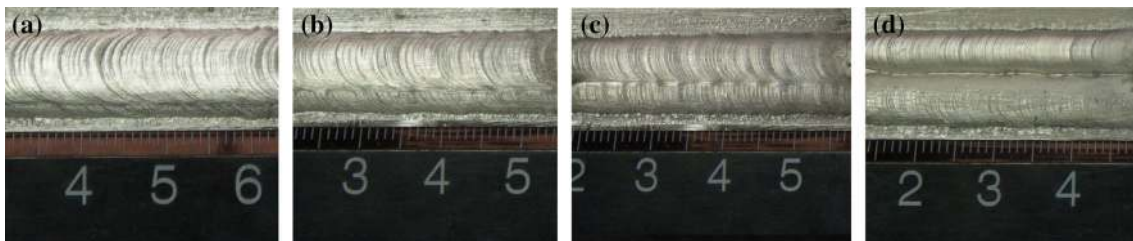


Fig. 5 Geometric configurations of the two-pass weld beads with different centerline spacing. (a) $0.5 W_1$, (b) $0.7 W_1$, (c) $0.8 W_1$ and (d) $0.9 W_1$ (W_1 is layer width)

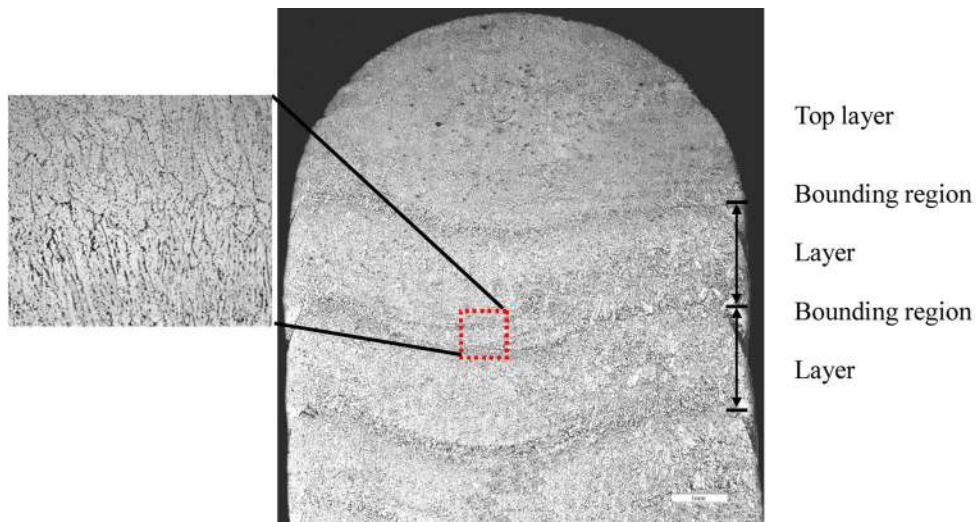


Fig. 6 Cross-sectional microstructure of deposited 5A06 aluminum alloy

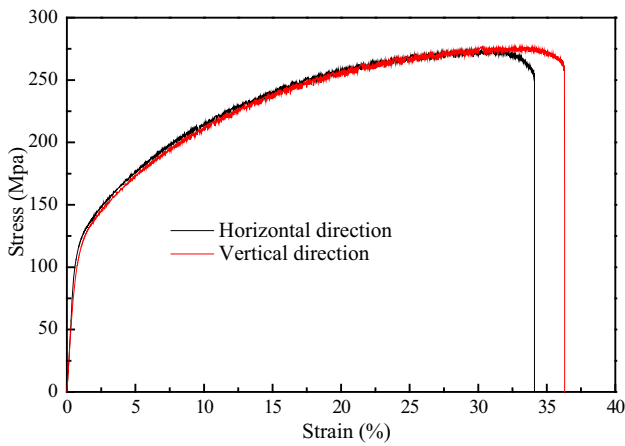
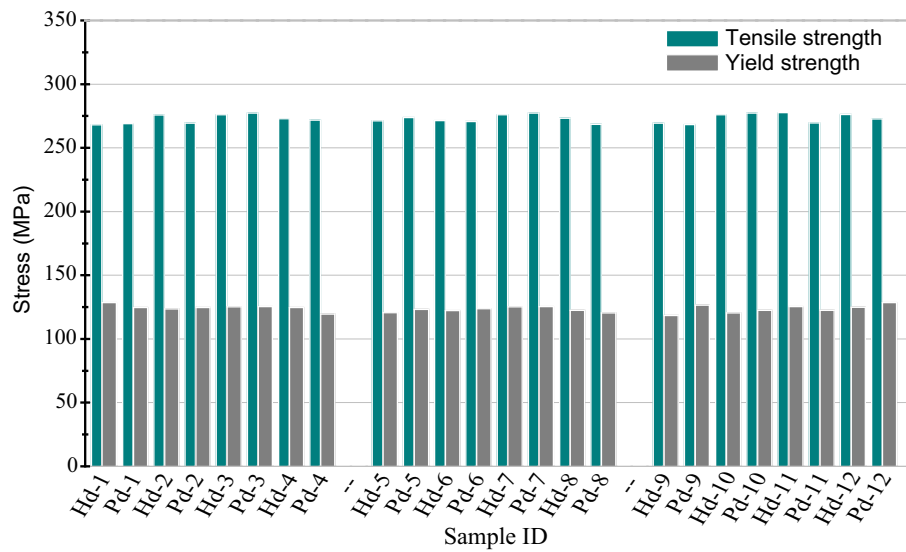


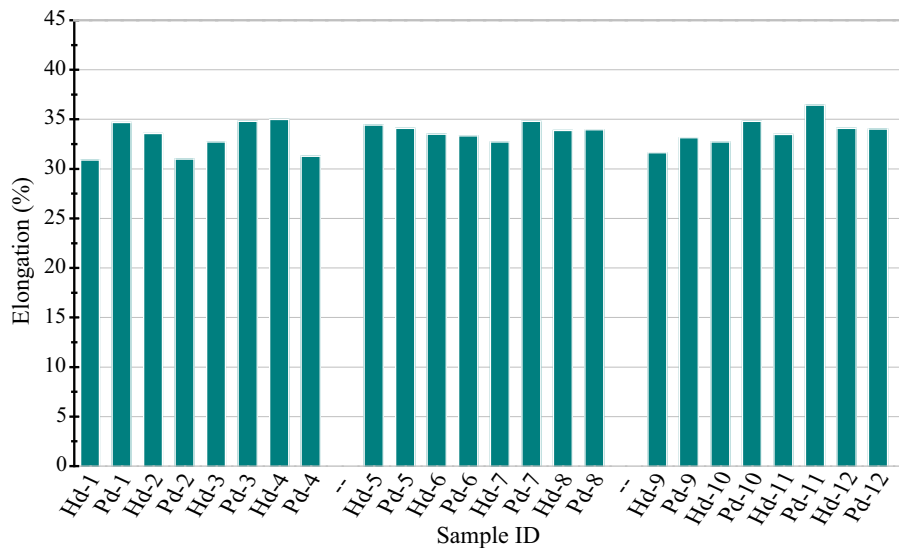
Fig. 7 Stress-strain curve of specimens along x and y directions

homogeneous, it has cooperative deformation behavior along force direction under axial tensile load. If cross-sectional microstructure is heterogeneous, localized tensile deformation in different regions is different accordingly, which will cause localized additional stress along loading direction, so it shows premature fracture under the same tensile strength. When considering global strain within gauge length, it shows minor effect. So it can be considered as isotropy in the direction of parallel and perpendicular to build direction under static tensile load. Varying the process parameters, how will the tensile property change? Figure 8 shows the yield and tensile strength of specimens in x and y directions deposited with varying process parameters.

The samples extracted from the single wall in x and y directions are isotropic when varying the process parameters. There is a little change in tensile strength when deposited with varying parameters, so is the yield strength. The average value of tensile and yield strength is 273 MPa and 124 MPa,



(a)



(b)

Fig. 8 Tensile test results of (a) tensile and yield strength and (b) elongation in x and y directions

respectively. Elongation in two directions is in the range of 31–36%, and the average value is 34%. The mean square error of the three tested mechanical parameters is 3.032, 2.216 and 1.374, respectively. So build direction and process parameters are not constraint conditions during formation of path planning, and loading in x and y directions is identical in service.

3.3 Tensile Properties in the Direction of Parallel and Perpendicular to Texture Orientation

Chemical composition of the deposited 5A06 aluminum alloy is investigated by means of EDS. The results are obtained by averaging five different positions along weld gun traveling direction, which demonstrates that the chemical composition of the deposited 5A06 aluminum alloy (Al-5.2 Mg, wt.%) has no difference from the raw materials (Al-5.8~6.8 Mg, wt.%). The single-wall part was deposited with unidirectional manner. So temperature gradient near the fusion line has similar orientation when the weld pool reaches steady state. In Fig. 9, it shows the similar texture orientation in each periodic inner layer.

Viewing from the side, it shows multi-layer structure. The columnar microstructures grow toward the weld gun travel direction with an angle of 18.6° from y direction. When varying the process parameters, it has similar columnar microstructures, and the only difference is the angle from y direction to the texture orientation, of which the value is in range of 11.6° (peak current 160 A, travel speed 0.25 m/min and wire feed speed 1.2 m/min) to 36.4° (peak current 120 A, travel speed 0.25 m/min and wire feed speed 2.0 m/min). The specimens were extracted from the single wall according to the angle. Figure 10 shows the tested stress-strain curve.

The yield strength, tensile strength and elongation of specimen parallel to texture orientation are 228 MPa, 87 MPa and 31%, respectively. In comparison, the specimens tested from the direction perpendicular to texture orientation exhibited higher yield strength of 104 MPa, tensile strength of 259 MPa and superior elongation of 37%. It shows a significant difference of tensile mechanical property between the two texture orientations. When varying the process parameters, Fig. 11 shows the tensile test results, and the anisotropy in the directions of parallel and perpendicular to texture orientation is obvious.

In Fig. 11(a), the average tensile strength of specimens in the direction of perpendicular to texture orientation is 251 MPa, and the mean square error is 10.504. The average yield strength of specimens in the direction of perpendicular to texture orientation is 101 MPa, and the mean square error is 8.920. The average tensile strength of specimens in the direction of parallel to texture orientation is 239 MPa, and the mean square error is 7.918. The average yield strength of specimens in the direction of parallel to texture orientation is 90 MPa, and the mean square error is 7.653. In Fig. 11(b), the average elongation of specimens in the direction of perpendicular to texture orientation is 34%, and the mean square error is 1.856. The average elongation of specimens in the direction of parallel to texture orientation is 37%, and the mean square error is 5.066.

Varying the process parameters, the tensile strength, yield strength and elongation have moderate fluctuation, which are expressed in larger value of mean square error. However, there is no systematic correlation between process parameters and its tensile test results. The average tensile strength in the direction of perpendicular to texture orientation is 13 MPa larger than the parallel one. The average yield strength in the direction of perpendicular to texture orientation is 11 MPa larger than the

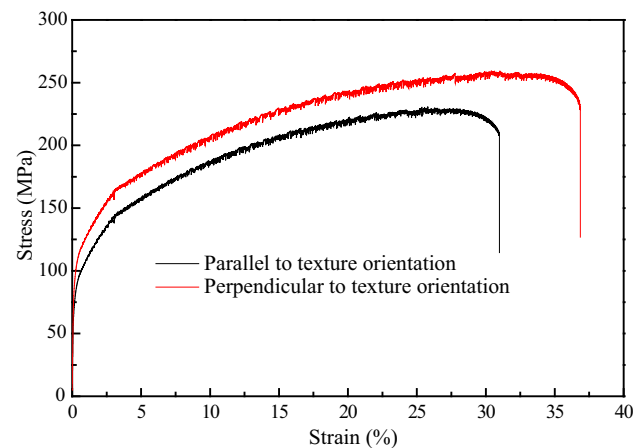


Fig. 10 Stress-strain curve of specimens along the direction of parallel and perpendicular to texture orientation

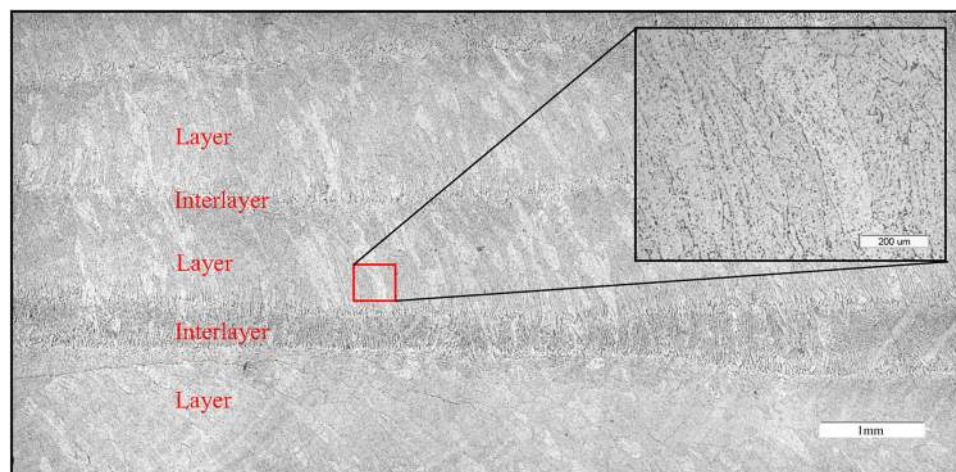


Fig. 9 Longitudinal section microstructures of as-deposited 5A06 aluminum alloy

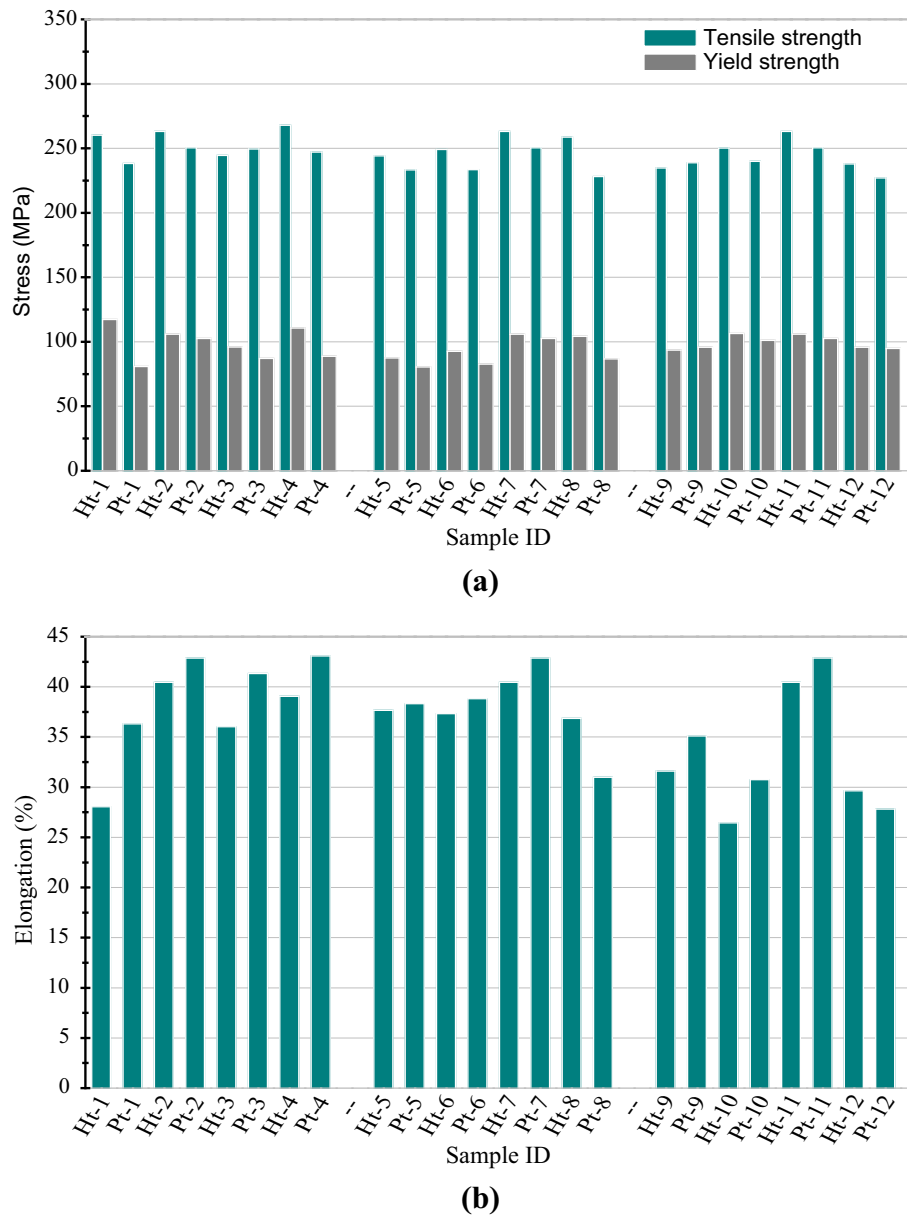


Fig. 11 Tensile test results of (a) tensile and yield strength and (b) elongation in the direction of parallel and perpendicular to texture orientation

parallel one. They further confirm the moderate anisotropy in two directions. That because of axial loading in the direction of perpendicular to texture orientation, a large number of grain boundaries become deformation resistance. So for the same strain, the stress is higher than loading along the other directions. Figure 12 shows longitudinal sectional microstructures along loading direction and its SEM fractograph.

Grain boundary sliding is a main mechanism to dominate the plastic deformation of aluminum. In Fig. 12(a), when loading in the direction of parallel to texture orientation, grain boundary slides along the texture orientation (i.e., loading direction) in the layers. In the bounding region, grain boundary slides along x direction. So the plastic deformation will lead to dislocation generation and piling up in the bounding region. With the strain increase, dislocation density increases rapidly. A main dislocation band with high dislocation density in bounding region will be generated during the loading process.

However, the region of high dislocation density is unstable. It is prone to crack nucleation and propagation. The cracks are torn or forming pores after the sample break. The pores can be found by observing SEM fractograph. When loading in the direction of parallel to texture orientation, as shown in Fig. 12(b), grain boundary sliding happens in bounding region firstly. In layers, tangential force along texture orientation is small, and only high-angle boundary can start to slide, which is accompanied by intragranular dislocation glide and climb. So the tensile strength is higher than tensile in the direction of parallel to texture orientation. The tensile sample fractures in the bounding region. Laminated tearing can be observed by observing SEM fractograph.

The tensile strength in y (or x) direction is 22 MPa higher than that in the direction of perpendicular to texture orientation and 34 MPa higher than that in the direction of parallel to texture orientation. So wire and arc additive manufactured

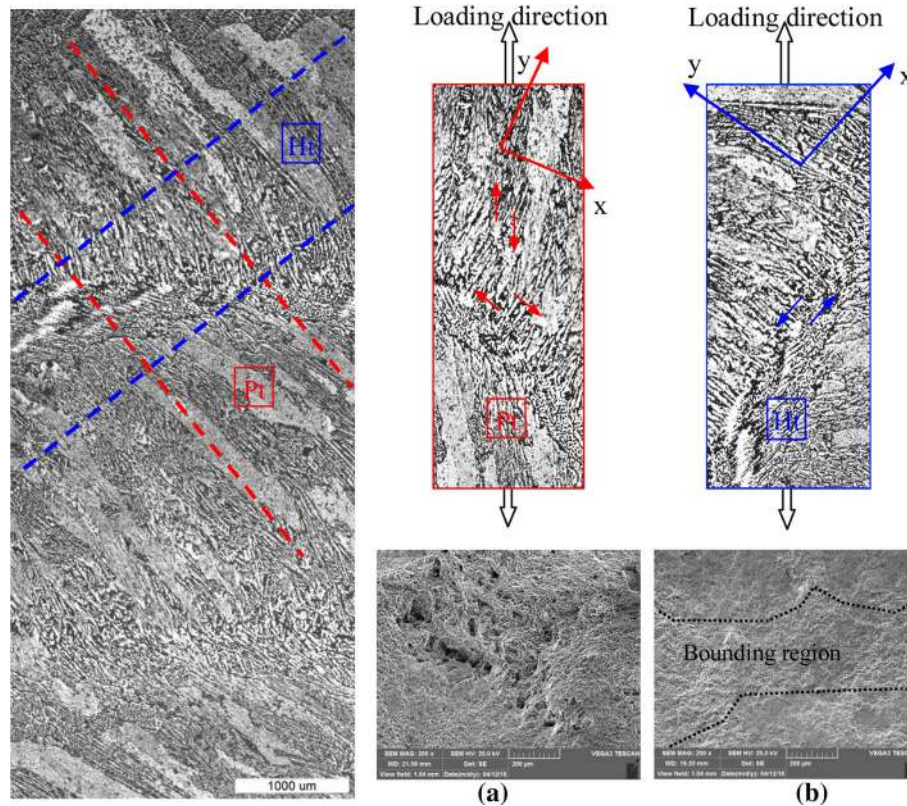


Fig. 12 Longitudinal section microstructures and SEM fractograph along loading direction. (a) In the direction of parallel to texture orientation and (b) in the direction of perpendicular to texture orientation

5A06 aluminum alloy also shows moderate anisotropy among y (or x) direction, directions of parallel to texture orientation and perpendicular one. In wire and arc additive manufacturing 5A06 aluminum alloy process, slicing along the plane perpendicular to primary loading direction is advisable because of the anisotropy, or else taking the minimum mechanical performance index as reference value to optimize geometric structure and size.

4. Conclusion

WAAM is just taken as a shaping method to facilitate forming the complex structure. More optimal structure design and more complex structure should be designed to give full play to the advantage of complex structure formation. That is, structure optimization for WAAM is gradually becoming an emerging research area. However, the constraint conditions of structure optimization for WAAM are unknown for most materials. This paper taking wire and arc additive manufacturing 5A06 aluminum alloy, for example, aims to clarify the geometric limitation and mechanical property index using experimental method. The following conclusions can be drawn.

- (1) Under the deposition parameters in the paper, angle exceeding 20° is preferable for WAAM. The initial and terminal sides of the angle will overlap if the angle is smaller than 20° . The minimum curvature radius that can be made by WAAM is 10 mm when the layer width is 7.2 mm. If the curvature radius is set to smaller than

this value, the inner outline will distort, which goes against the following layer deposition.

- (2) In x (horizontal) and y (vertical) direction, the tensile test results show isotropy. The average value of the tensile strength, yield strength and elongation is 273 MPa, 124 MPa and 34%, respectively.
- (3) In the direction of parallel and perpendicular to texture orientation, the tensile properties are anisotropic. The average tensile strength and yield strength of specimens in the direction of perpendicular to texture orientation are 251 and 101 MPa. The average tensile strength and yield strength of specimens in the direction of parallel to texture orientation are 239 and 90 MPa. The average elongation in the direction of parallel and perpendicular to texture orientation is 37 and 34%.

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