IMPROVED MICROSTRUCTURE AND INCREASED MECHANICAL PROPERTIES OF ADDITIVE MANUFACTURE PRODUCED TI-6AL-4V BY INTERPASS COLD ROLLING.

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Abstract

Distortion, residual stress and mechanical property anisotropy are current challenges in additive manufacturing (AM) of Ti–6Al–4V. High-pressure, interpass rolling was applied to linear AM parts and resulted in a change from large columnar prior β grains to a completely equiaxed microstructure with grains as small as 89 µm. Moreover, α laths thickness was also reduced to 0.62 µm. The change in material microstructure resulted in a substantial improvement of all mechanical properties tested, which were also totally isotropic. In rolled specimens, maximum measured strength and elongation were 1078 MPa and 14% respectively, both superior to the wrought material. Distortion was reduced to less than half. Rolling proved to be a relatively easy method to overcome some of the critical issues which keep AM from full industrial implementation.

1 Introduction

The anisotropy of mechanical properties is one of the issues currently affecting additive manufacturing (AM) [1, 2]. Due to solidification characteristics of Ti–6Al–4V, parts microstructure is characterised by large columnar prior β grains, parallel to the thermal gradient, hence orientated along the vertical direction. These grains are also strongly textured [3].

Residual stress and distortion are also present challenges for AM [4, 5]; at the moment, they are overcome with post deposition heat treatments [6]. Heat treatments also influence the microstructure (consequently the mechanical properties) and result in an increase of the elongation without compromising the ultimate tensile strength [7]. However, anisotropy is not addressed.

In welding research, many techniques have been investigated to mitigate residual stress and distortion, including tensioning [8], peening [9, 10] and rolling [11, 12]. The latter can be implemented easily and was attempted on steel AM structures for the first time by Colegrove et al. [4], resulting in a substantial reduction in distortion and residual stress, as well as grain refinement. Hence the same technique has been applied on Ti–6Al–4V deposits to investigate whether similar results could be achieved.

2 Experimental methods

A standard TIG power source (Lincoln Electric Invertec V310–T) was fitted onto a in-house designed rolling rig, as shown in Fig. 1. This deposition process belongs to wire+arc additive manufacturing (WAAM), which in general consists in the use of arc welding tools for additive manufacturing purposes. Linear structures were deposited onto a 6 mm thick substrate, using the parameters listed in Table 1. Rolling started and finished 35 mm within the deposit, and was done between passes, with a speed of $3\,\mathrm{mm\,s^{-1}}$ after the material had cooled to room temperature. Three loads were applied: 50 kN, 75 kN and 100 kN. Walls built for microstructural analysis, as well as measuring out-of-plane distortion and geometric characteristics, were 370 mm long. Parts were sectioned at three locations to increase measurement reliability. The same cross sections were used for microhardness measurements (every 0.5 mm starting from 2.5 mm into the base plate with a load of 500 g and indentation time of 15 s). Three additional walls were built for tensile testing [13]; dog bone specimens were extracted in both vertical and horizontal directions and had a length of 120 mm, with a gauge of 24 mm × 6 mm × 4 mm.

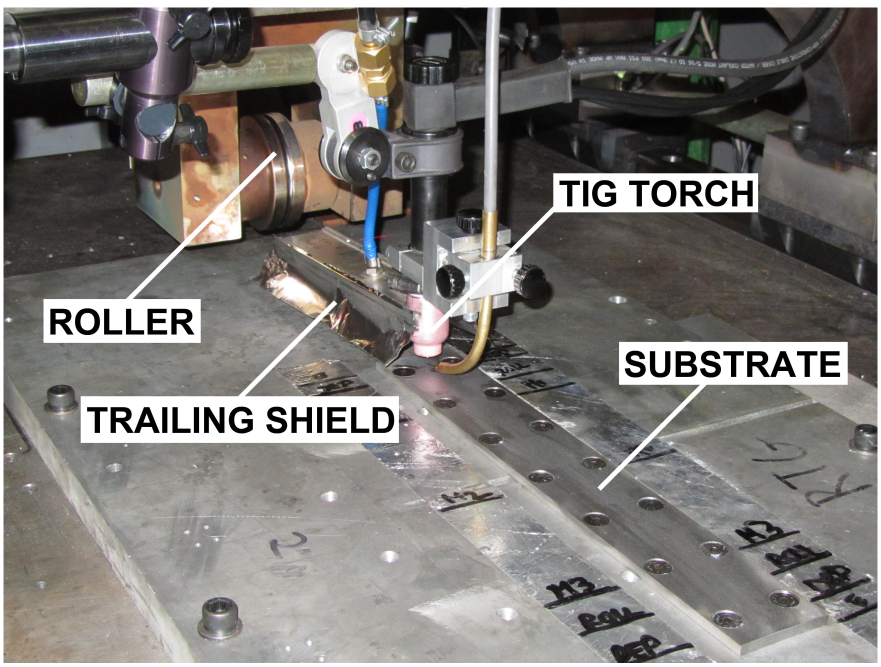


Figure 1: Experimental setup for rolling investigation.

Table 1: Deposition parameters

Wire feed speed	$1.6\,\mathrm{m\,min^{-1}}$
Travel speed	$4.5\,\mathrm{mm\,s^{-1}}$
Peak current	150 A
Background current	70 A
Average current	110 A
Pulse duration	0.05 s
Frequency	10 Hz

3 Experimental results and discussion

3.1 Distortion and geometry

Distortion reduced with increased load: the maximum out-of-plane distortion of the control specimen was 7 mm, and it decreased to 5 mm with a load of 50 kN, and to 3 mm with a load of 75 kN. The plastic deformation induced by rolling resulted in changes to the specimens' width and height, the former increasing with the load, the latter showing an opposite behaviour (Table 2). It's worth noting the reduction in the standard deviation of layer height, which would aid industrial implementation of AM as it reduces variability.

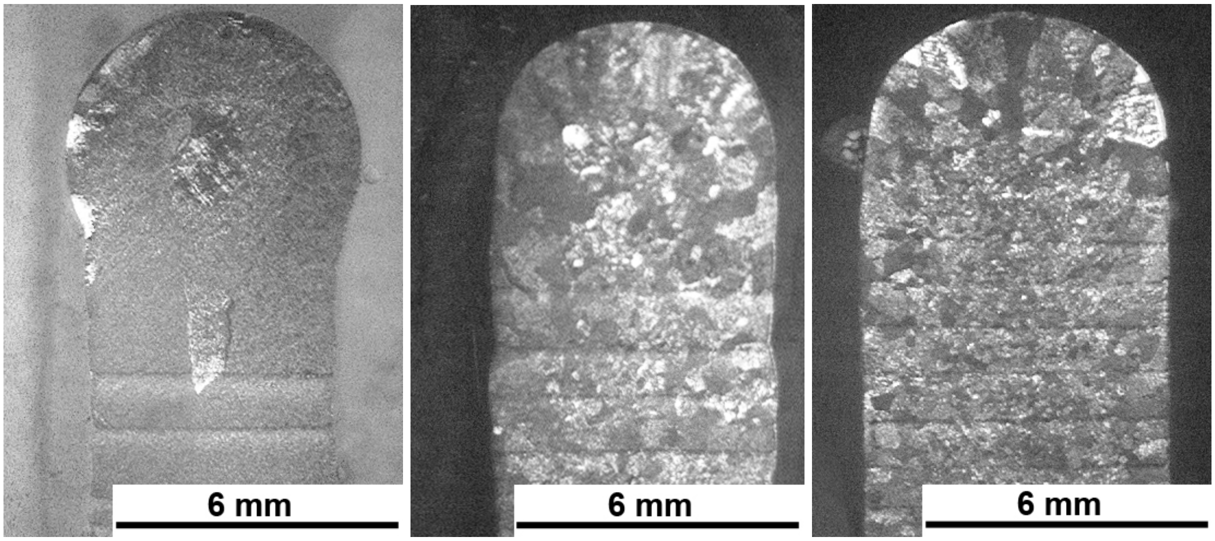
Table 2: Changes in wall width and layer height.

	Wall width		**Layer height**	
	Average	Std. dev.	Average	Std. dev.
Control	5.71 mm	0.18	1.13 mm	0.19
50 kN	6.17 mm	0.11	1.04 mm	0.12
75 kN	6.71 mm	0.14	0.93 mm	0.09

3.2 Microstructure

All specimens are characterised by a Widmänstatten microstructure, however the prior β grains configuration differs substantially between unrolled and rolled samples (Fig. 2). The former showed the columnar grains configuration that is typical of AM deposits, with elongated grains a few millimetre wide and a length that often traverses the whole component (Fig. 2a). The latter, instead, were characterised by a refined microstructure with equiaxed prior β grains. In fact, when rolling at 50 kN the average grain size was 125 µm (Fig. 2b), and for the 75 kN specimen it was 89 µm (Fig. 2c). It must be said that even the rolled specimens had a region with columnar prior β grains, specifically the top ca. 2 mm. This region was also rich in martensite, in all specimens, rather than Widmänstatten which is observed below. The horizontal bands that corresponded to the deposition of each layer were observed in all specimens. For an explanation of the origin of these bands, please refer to Martina et al. [14].

In terms of α phase, rolled specimens were still characterised by the repetitive pattern in α lamellae thickness, within each horizontal band [14, 15]. In fact, α lamellae thickness was minimum around the bottom of each band (i.e. near the base plate), and increased gradually until it reached its maximum just before the next band started (i.e. towards the top of the wall). However, rolling resulted in a reduced α lamellae average thickness: for the control specimen it was 0.79 µm, for a rolling load of 50 kN it was 0.66 µm, and for the 75 kN specimen it was down to 0.62 µm. The nucleation of α phase lamellae starts at grain boundaries; as the part cools down, lamellae grow until they hit each other, and then new lamellae start growing perpendicular to the already developed ones, until an equilibrium fraction of α phase is reached [16, pp. 32–33]. Given the refined prior β grains, it is possible that the distance covered by α lamellae before they hit each other was shorter, hence their overall size was reduced.



(a) (b) (c)

Figure 2: Optical microscopy images of top areas from (a) control specimen, (b) specimen rolled at 50 kN and (c) specimen rolled at 75 kN.

3.3 Mechanical properties

Rolling resulted in an improvement of all mechanical properties tested, which were always higher for both horizontal and vertical directions, apart from the elongation of the vertical unrolled specimens. In Fig. 3 tensile test results from the present research are compared against the wrought material tested by Wang et al. [2], and the specifications minima prescribed by ASTM B265 – 09a [17]. For the specimen rolled at 75 kN all properties were better than the wrought material. The hardness values were 374 HV and 377 HV, for the 50 kN and 75 kN specimens, respectively; both values are higher than the unrolled sample (367 HV).

The improvement in strength and hardness could be due to two reasons. First, the refinement in the α phase is associated with an improvement of these two mechanical properties, at least for the cooling rates experienced in the WAAM process [18]. Second, each rolling pass induces a certain amount of cold work. Even if the subsequent deposition effectively has an annealing effect, this could be only partial. In fact, when rolling at 100 kN was attempted, the part fractured during rolling of the seventh layer.

As for the elongation, a third factor must be considered: the refinement of prior β grains, which has a detrimental effect of this property (so does work hardening). On the contrary, the reduction in α lamellae thickness is beneficial [18], and from case to case one of these factors would prevail over the others. For instance, in the case of the horizontal direction, elongation firstly decreases (from control to 50 kN) then increases (from 50 kN to 75 kN). Clearly for the 50 kN specimen, the contribution of cold work and reduced prior β grain size is dominant; however, for the 75 kN specimen the reduction in α lamellae thickness must be the factor with the greater effect, given that the elongation increases, even if only slightly. In the vertical direction the refinement of prior

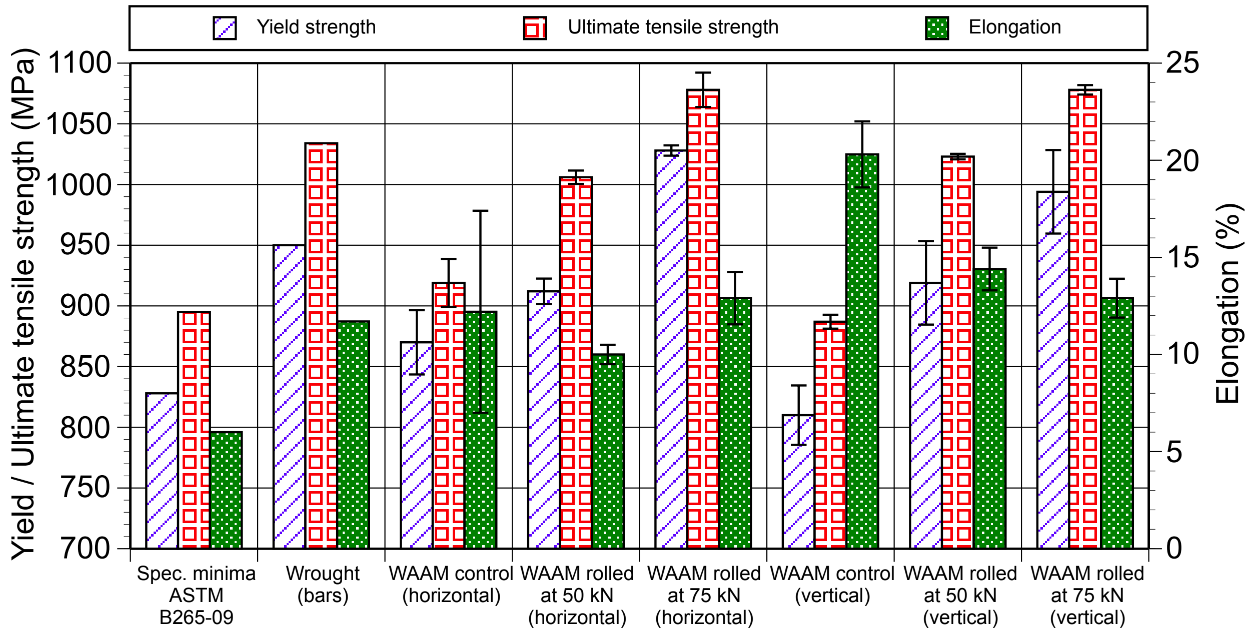


Figure 3: Comparison of rolled WAAM specimens against unrolled ones (error bars indicate standard deviation), specification minima [17], and wrought Ti–6Al–4V [2].

β grains gives the dominant contribution: a much larger reduction in grain size is observed along this direction, and elongation always decreases with the load.

Finally it is worth mentioning that cold work is the least important of the causes. If this wasn't the case, a larger reduction in elongation would be seen in the 75 kN specimen, which had the highest strain. However elongation decreases marginally in the vertical direction and surprisingly increases in the horizontal one, which suggests that microstructural changes dominate over cold work.

The most important finding of the present research is possibly the achievement of a totally isotropic mechanical behaviour. In fact, already for a load of 50 kN the difference between the properties in the two tested direction is minimal; this is because even if the 50 kN specimen was already characterised by an equiaxed prior β grains structure, possibly its texture wasn't completely randomised [19] — differently from the 75 kN one, whose behaviour is completely isotropic.

4 Conclusions

Rolling of Ti–6Al–4V wire+arc additively manufactured walls resulted in:

- reduced distortion, because of changes in the geometry of deposits and most likely reduction in residual stress;
- reduced variability of layer height;

- refined prior β grains and α lamellae, and change from columnar to equiaxed microstructure due to recrystallisation of the β phase;
- improved mechanical properties — strength, hardness and elongation were almost always better in the rolled case, and properties of the 75 kN specimen were even better than the wrought material ones;
- isotropic mechanical properties.

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References

[1] B. Baufeld, O. Van der Biest, and R. Gault. Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: microstructure and mechanical properties. *Materials & Design*, SUPPL. 1:S106–S111, 2009.

[2] F. Wang, S.W. Williams, P. Colegrove, and A.A. Antonysamy. Microstructure and Mechanical Properties of Wire and Arc Additive Manufactured Ti-6Al-4V. *Metallurgical and Materials Transactions A*, 44(2):968–977, 2013.

[3] B. Baufeld, O. Van der Biest, and S. Dillien. Texture and crystal orientation in Ti-6Al-4V builds fabricated by shaped metal deposition. *Metallurgical and Materials Transactions A*, 41(8):1917–1927, Aug 2010. doi: 10.1007/s11661-010-0255-x.

[4] P.A. Colegrove, H.E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash, and L.D. Cozzolino. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *Journal Of Materials Processing Technology*, 213(10):1782–1791, October 2013.

[5] J. Ding, P. Colegrove, J. Mehnen, S. Ganguly, P. M. Sequeira Almeida, F. Wang, and S. W. Williams. Thermo-mechanical analysis of Wire and Arc Additive Layer Manufacturing process on large multi-layer parts. *Computational Materials Science*, 50(12):3315–3322, December 2011.

[6] S. Akula and K.P. Karunakaran. Hybrid adaptive layer manufacturing: An Intelligent art of direct metal rapid tooling process. *Robotics And Computer-Integrated Manufacturing*, 22(2): 113–123, 2006.

[7] B. Baufeld, E. Brandl, and O. Van der Biest. Wire based additive layer manufacturing: Comparison of microstructure and mechanical properties of Ti–6Al–4V components fabricated by laser-beam deposition and shaped metal deposition. *Journal of Materials Processing Tech.*, 211(6):1146–1158, June 2011.

[8] D.G. Richards, P.B. Prangnell, S.W. Williams, and P.J. Withers. Global mechanical tensioning for the management of residual stresses in welds. *Materials Science and Engineering A*, 489(1-2):351–362, 2008.

[9] S.D. Cuellar, M.R. Hill, A.T. DeWald, and J.E. Rankin. Residual stress and fatigue life in laser shock peened open hole samples. *International Journal of Fatigue*, 44(C):8–13, November 2012.

[10] P.J. Withers and H.K.D.H. Bhadeshia. Overview - Residual stress part 1 - Measurement techniques. *Materials Science And Technology*, 17(4):355–365, 2001.

[11] H.E. Coules, P. Colegrove, L.D. Cozzolino, S.W. Wen, S. Ganguly, and T. Pirling. Effect of high pressure rolling on weld-induced residual stresses. *Science and Technology of Welding & Joining*, 17(5):394–401, 2012.

[12] H. E. Coules. Contemporary approaches to reducing weld induced residual stress. *Materials Science And Technology*, 29(1):4–18, January 2013.

[13] BS EN 2002–1:2005. Metallic materials – Test methods – Part 1: Tensile testing at ambient temperature, 2005.

[14] F. Martina, J. Mehnen, S. W. Williams, P. Colegrove, and F. Wang. Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V. *Journal of Materials Processing Technology*, 212(6):1377–1386, June 2012.

[15] S.M. Kelly and S.L. Kampe. Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part I. Microstructural characterization. *Metallurgical And Materials Transactions A*, 35A(6):1861–1867, 2004.

[16] G. Lütjering and J.C. Williams. *Titanium*. Springer, second edition, 2007.

[17] ASTM B265 – 09a. Standard Specification for Titanium and Titanium Alloy Strip, Sheet, and Plate, 2009.

[18] G. Lütjering. Influence of processing on microstructure and mechanical properties of $(\alpha+\beta)$ titanium alloys. *Materials Science and Engineering A*, 243(1-2):32–45, 1998.

[19] A.A. Antonysamy, F. Martina, P.A. Colegrove, S.W. Williams, and P. Prangnell. The Effect of Integrating Rolling Deformation with Wire Arc Additive Manufacture of Ti–6Al–4V on Grain Size and Texture Refinement. *Metallurgical and Materials Transactions A*, SUBMITTED, 2013.

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