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Full Length Article

Interpass rolling of Ti-6Al-4V wire + arc additively manufactured features for microstructural refinement

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ABSTRACT

In-process deformation methods such as rolling can be used to refine the large columnar grains that form when wire + arc additively manufacturing (WAAM) titanium alloys. Due to the laterally restrained geometry, application to thick walls and intersecting features required the development of a new 'inverted profile' roller. A larger radii roller increased the extent of the recrystallised area, providing a more uniform grain size, and higher loads increased the amount of refinement. Electron backscatter diffraction showed that the majority of the strain is generated toward the edges of the rolled groove, up to 3 mm below the rolled surface. These results will help facilitate future optimisation of the rolling process and industrialisation of WAAM for large-scale titanium components.

1. Introduction

Wire + arc additive manufacturing (WAAM) is a 3D printing technology capable of meeting the needs of industry for producing metre-sized metallic components [1]. These components are produced through layer by layer material deposition, utilising an arc-based heat source, such as plasma or Metal Inert Gas deposition, and wire as feedstock [2,3]. Fig. 1 illustrates the process.

Owing to the many benefits of WAAM (e.g. high deposition rate, manufacturing cost reduction and reduced lead time) it is finding increasing interest for the manufacture of aircraft structural components – particularly for Ti-6Al-4V. This is primarily due to titanium and its alloys being extremely expensive in terms of purchase cost (> £70 kg^{-1}), energy consumption (> 500 MJ kg^{-1}) and CO_2 emissions (> 40 kg kg^{-1}) [4]. Typically, Ti-6Al-4V aircraft structural components are machined from oversized ingots, forgings and extrusions. Not only is this a time consuming process (e.g. waiting for forging dies to be manufactured) but it is also expensive due to the proportionally large amount of material that is purchased compared to the amount that remains after machining. The buy-to-fly (BTF) ratios of components manufactured using this approach can be as poor as 20:1. WAAM reduces the material required to make a component by producing near-net-shape preforms, which are subsequently machined to the desired dimensions. This brings substantial improvements to the BTF ratios (typically 1.5), which significantly reduce the manufacturing cost [2].

For successful implementation of WAAM the material properties should ideally meet or exceed those from the wrought material. This can be difficult due to the very different manufacturing route that AM parts undergo – normally they experience a series of thermal cycles with ever decreasing peak temperatures. For Ti-6Al-4V WAAM the small freezing range and epitaxial growth results in large, columnar prior β grains that have anisotropic properties, which are undesirable for aerospace applications [2,5].

Colegrove et al. [6] described how interpass rolling of the deposited layers can improve the mechanical properties of Ti-6Al-4V WAAM deposits through microstructural refinement of the prior β grains. Interpass rolling increased both the yield and tensile strengths by 18–25% while eliminating material anisotropy. An equiaxed prior β microstructure that can be as small as 60 μm is produced despite the induced strain being relatively modest (7–20%) [9,10]. Interpass rolling also improves fatigue properties due to the high proof strength, fine Widmanstatten basket-weave microstructure and isotropic texture with a small prior β grain size [6,7]. The improvement may also be due to the reduced incidence of porosity [8] which is known to limit fatigue performance [9].

An early investigation showed that prior β refinement initiates on

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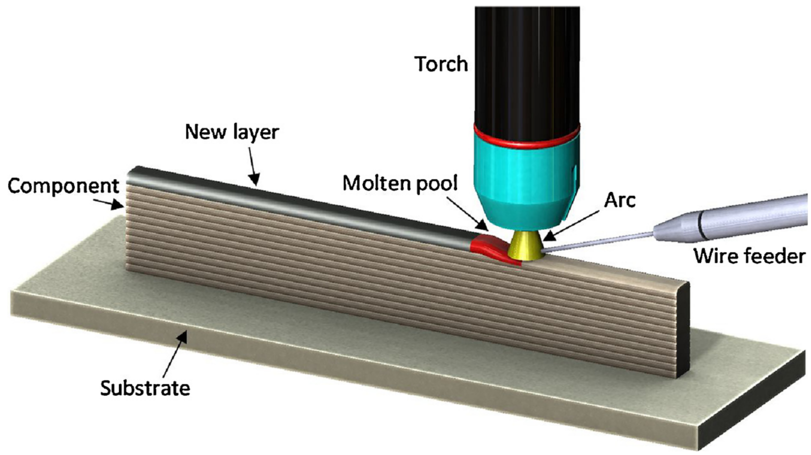

Fig. 1. Illustration of the WAAM process.

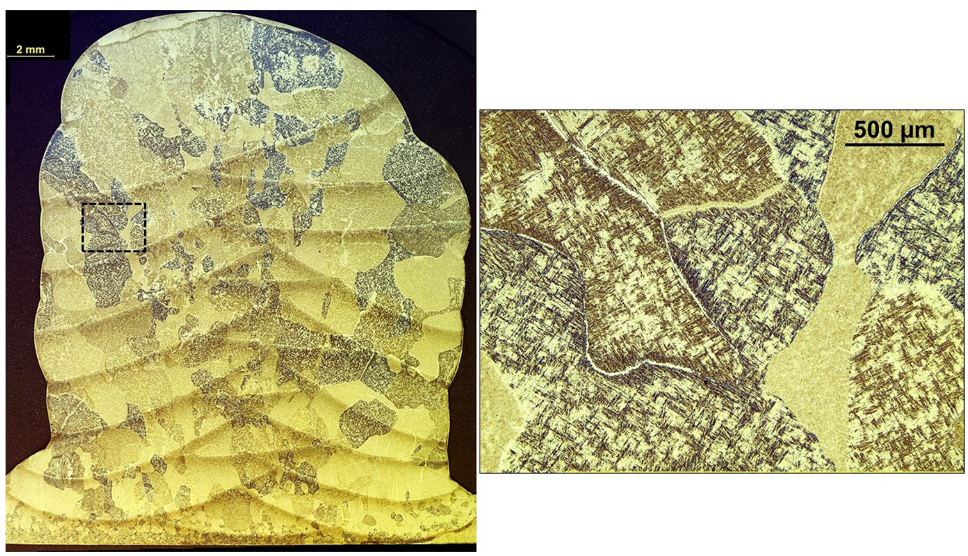

Fig. 2. A macrograph of a thick Ti-6Al-4V WAAM wall that was rolled with a flat roller at 75 kN. Notice that there is little prior β grain refinement.

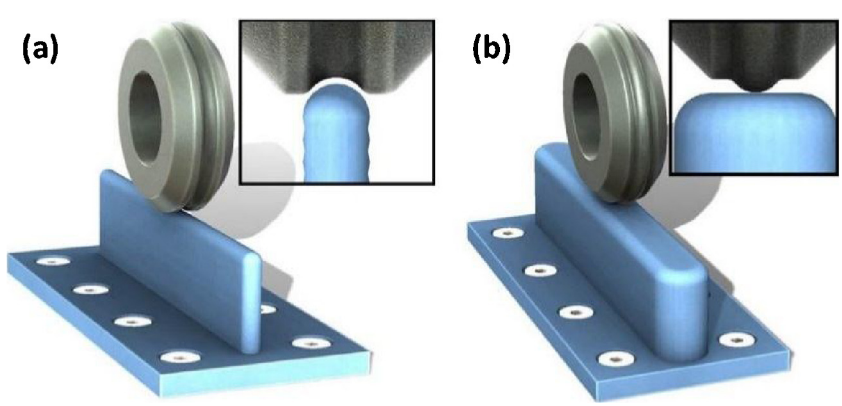

Fig. 3. Schematic diagram of the main rolling methods: (a) vertical with a profiled roller; (b) rolling with an inverted profiled roller for thick sections and intersections.

twinned α colonies upon heating [10], but more recent work reports that the new β orientation originate from twinned β cells; because the β phase grows from residual β between the α laths before new β can nucleate in pure (i.e. twinned) α at higher temperature [11]. The large number of β nuclei with random orientation prevent the re-establishment of the previous columnar microstructure.

A number of different rolling methods have been developed. Interpass rolling has predominantly been applied to thin (< 10 mm) walls and the rollers often have a similar profile to the deposit [7,12] (Fig. 3(a)). Martina et al. [7] demonstrated that similar levels of refinement were possible with a flat roller, however the grains were smaller in the centre of the wall due to the concentration of strain in this region. Applications that involve thin walls have very little lateral restraint, so strain can be relatively easily induced within the material: