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Viewpoint paper

Application of bulk deformation methods for microstructural and material property improvement and residual stress and distortion control in additively manufactured components

Paul A. Colegrove [a,*], Jack Donoghue [b], Filomeno Martina [a], Jianglong Gu [c], Philip Prangnell [b], Jan Hönnige [a]

[a] Welding Engineering and Laser Processing Centre, Cranfield University, Building 46, Cranfield MK43 0AL, UK
[b] School of Materials, University of Manchester, Manchester M13 9PL, UK
[c] College of Materials Science and Engineering, Yanshan University, Qinhuangdao 066004, PR China

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ABSTRACT

Many additively manufactured (AM) materials have properties that are inferior to their wrought counterparts, which impedes industrial implementation of the technology. Bulk deformation methods, such as rolling, applied in-process during AM can provide significant benefits including reducing residual stresses and distortion, and grain refinement. The latter is particularly beneficial for titanium alloys where the normally seen large prior β grains are converted to a fine equiaxed structure – giving isotropic mechanical properties that can be better than the wrought material. The technique is also beneficial for aluminium alloys where it enables a dramatic reduction in porosity and improved ductility.

1. Background

Additive manufacturing (AM) techniques currently have a high profile within industry and the wider public because of the perception that almost anything can be manufactured by such processes. One important aspect that is often overlooked is that the material properties can be inferior to those of a conventional wrought product, which can limit the applicability of AM processes. In addition, residual stress and distortion can be significant which can result in the part being out of tolerance and can impede performance.

In the related field of welding, rolling of weld beads is an extremely effective way of reducing both the residual stresses and distortion [1]. More recently this concept has been applied to large-scale additively manufactured parts in two parallel activities: one at Cranfield University in the UK and the other at Huazhong University in China. The activity at Cranfield was first reported by Colegrove et al. [2], where the technique was applied between passes of an AM wall, after the material was allowed to cool to near-ambient temperature. The parallel activity in China was first reported by Zhang et al. [3] and has focussed on 'in-situ' rolling (or hybrid deposition and micro rolling (HDMR) [4]) which was applied directly behind the deposition torch. These two different approaches are shown schematically in Fig. 1 (a) and (b). The aims of the activities were to improve the microstructure and texture [4–6], properties [7,8], geometry [8], and the residual stress and distortion of the AM components [2,9].

Based on the work of these two groups, this viewpoint provides a review of the progress to date and potential for the application of bulk deformation (rolling) methods during AM to improve the performance of large scale AM components. The use of surface deformation techniques such as peening to improve fatigue and/or corrosion performance will not be considered. Coincidentally, both research groups used the Wire + Arc Additive Manufacturing (WAAM) process where common arc welding processes, such as metal inert gas, tungsten inert gas and plasma are used to produce large, meter-scale parts relatively cheaply with high deposition rates. A review of wire-feed AM technologies including WAAM is provided by Ding et al. [10].

2. Residual stress and distortion control

When material is deposited during AM, it expands due to the heat provided by the deposition process, which causes compressive plastic deformation ahead of the moving heat source. On cooling, the material contracts which results in the generation of an almost uniform tensile residual stresses in the longitudinal (deposition) direction along the height of the wall while the sample is attached to the base plate and clamped. After unclamping, the component distorts and there is a redistribution of the residual stress so that the net bending moment across a section becomes zero [2]. A typical plot of the residual stress in an unrolled low carbon steel 'control' sample is shown in Fig. 2(a).

* Corresponding author.
E-mail address: p.colegrove@cranfield.ac.uk (P.A. Colegrove).

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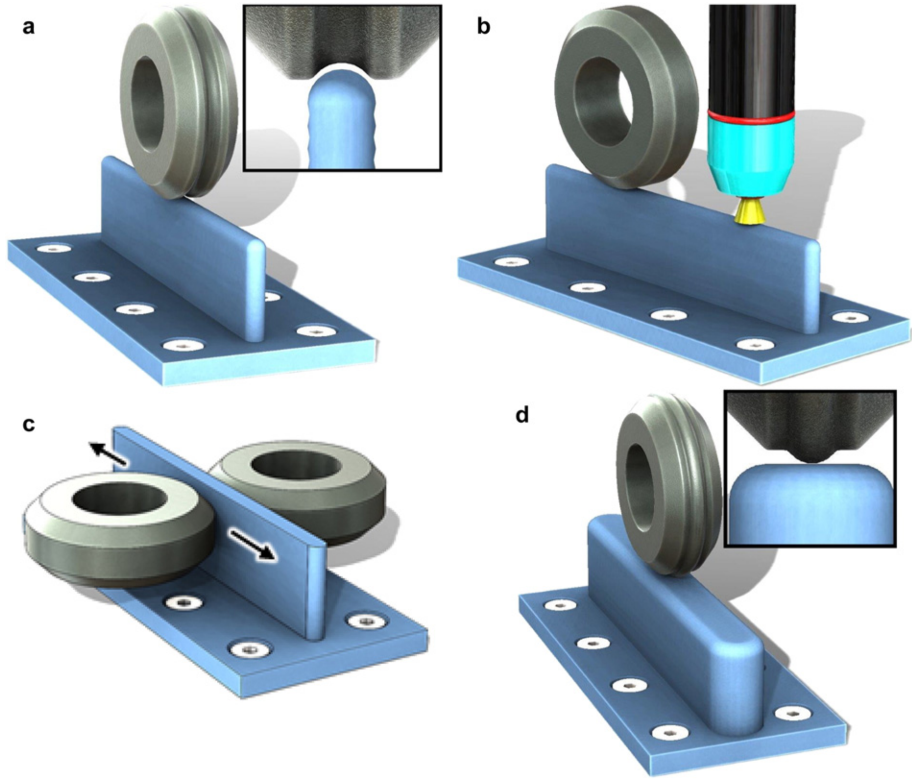

Fig. 1. Schematic diagram of the main rolling methods: (a) vertical with a profiled roller; (b) in-situ rolling; (c) pinch rolling (d) rolling with an inverted profiled roller for thick sections and intersections.

In an early study [2] where rolling was applied to an additively manufactured low carbon steel single pass wall, several different rolling strategies were investigated: rolling with a profiled roller after every deposited layer, rolling just the last layer (LL), rolling every fourth layer (4L) and rolling in-situ (IS). In addition, a slotted roller was investigated which restrained the material laterally. The residual stress results are shown in Fig. 2(a) and the distortion is shown in Fig. 2(b). Although there was a reduction in the residual stress, particularly at the interface with the substrate, the reduction was far less significant than that observed when rolling is applied to welded joints. Rolling is applied repetitively to many layers in the AM process whereas in welding it is applied once to a single pass weld. Therefore, even though significant compressive stresses may be produced underneath the material that has just been rolled at the top of an AM wall (Fig. 2(a)), subsequent deposition of the next layer will replace this with tensile stresses. Hence, there is a competition between the size of the regions influenced by the rolling and deposition processes and the final value will be the one that influences the greater volume of material. The residual stress measurements to date indicate that the deposition process has the greater influence (e.g. Fig. 2), although rolling each layer is able to reduce their magnitude. Another important difference is that welded joints are restrained laterally, so the vertical deformation of the roller causes tensile plastic strain in the longitudinal direction which helps to remove the residual stresses in this direction. In comparison, when rolling additively manufactured walls, there is little lateral restraint with the standard profiled roller so most of the plastic strain occurs in the transverse plane with little in the rolling/torch travel direction [6]. Therefore, a significant amount of residual stress remains and it is difficult to fully

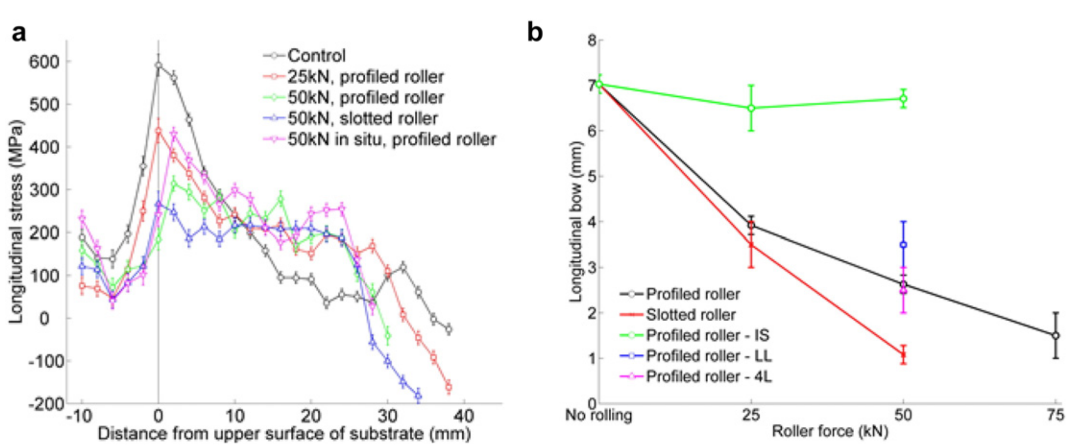

Fig. 2. (a) Residual stresses measured in unclamped steel specimens after rolling with profiled and slotted rollers at different loads; (b) corresponding distortion measurements at different loads. Note IS = in-situ, LL = rolling of last layer only, and 4L = rolling every fourth layer. Full results are reported in Colegrove et al. [2].

eliminate distortion. This study has, however, demonstrated that a slotted roller, which restrains the lateral movement of the material, can overcome this problem by providing a greater region of compressive stress at the top of the deposit (Fig. 2(a)) giving greater reductions in both the residual stress and distortion. In-situ rolling was also investigated and it had no effect on the distortion [2].

Similar reductions in residual stresses have been observed when WAAM processing of titanium alloys by Martina et al. [9], although the overall stresses in this material were reported to be much lower in comparison to the yield strength. This work included contour method results which also revealed a slight reduction of the longitudinal tensile stresses along the sides of the wall which may be beneficial for performance.

Because of the advantage of laterally restraining the material in AM, noted above, side rolling has recently been applied to the WAAM process by Hönnige et al. [11], while building a Ti-6Al-4V single pass wide wall. In this study, the specimen was rigidly clamped during deposition to prevent distortion and a vertical wall was deposited without application of rolling. The specimen was then removed and rotated 90°, while still clamped to a thick aluminium block to prevent distortion as shown in Fig. 3(a). This method was more effective in reducing the distortion and residual stress, which could be nearly eliminated with the application of the optimum load as shown in Fig. 3(b-d). The bulk strains were not measured in this work, however, the load did not cause any large-scale plastic deformation as is typical with vertical rolling.

3. Microstructural refinement

In the initial study on the application of deformation by rolling in the WAAM process to steels, reported above, [2] a modest level of grain refinement was observed following the application of a 50 kN load which provided a 50% strain in the 5 mm thick wall. In contrast, when applied to titanium alloys like Ti-6Al-4V even modest plastic strains of 7–20% [6] have been found to provide a very significant effect on the prior β -grain structure and texture [5,6].

In the WAAM processes when using a Ti-6Al-4V feedstock there is a strong tendency to develop very coarse prior columnar β-grain structures that can extend through many added layers with an associated {001} fibre texture, which can be detrimental to the mechanical properties because it leads to significant anisotropy in AM components [5,12]. Interpass cold work has been found to be surprisingly effective at disrupting the formation of this undesirable microstructure and results in a refined, equiaxed, prior β microstructure with a weakened crystallographic texture [6,13], as shown in Fig. 4.

The columnar β grain structure normally seen in AM with titanium forms as a result of the difficulty of obtaining sufficient constitutional super cooling for nucleation ahead of the growth front in a moving melt pool process, which results in the β grains regrowing epitaxially up through the melt pool from the re-melted previous layer. These columnar grains grow with the ⟨100⟩ aligned normal to the melt pool surface, since this is the preferred solidification direction in bcc titanium [5,12]. The cooling rates through the β-transus in the WAAM process are ~10^2 K/s which leads to a predominantly very fine Widmanstätten α lath microstructure with a small amount of fine residual β retained between the laths [6]. Transformation also weakens the texture owing to the twelve orientations possible for the α phase variants from the Burger's orientation relationship [5,12]. The residual β provides a 'memory' of the previous high-temperature microstructure and re-grows with the same local orientation when the material is reheated above the β-transus by the next deposited layer. This effect ensures the continued development of a coarse columnar β grain structure as it is reformed below the fusion boundary of each pass as the heat source approaches and acts as the substrate for solidification [5,12]. As can be seen in Fig. 2 this columnar structure can be fully eliminated by applying in-process rolling [5,13].

With the rolled WAAM samples it was found that the level of prior β grain refinement is related to the applied load; with a rolling reduction of ~20% leading to a refined average grain diameter of ~90 μm [5,6]. However, refinement was still observed with surprisingly modest reductions of ~8%. Rolling is the last process to be implemented and these small strains provide little visible change to the macrostructure, although some twinned alpha is observed in the microstructure as shown in Fig. 5. Donoghue et al. [5] has also found that the region of microstructural refinement correlates well with the plastic strain distribution imparted by the roller [5,6] and showed that the plastic deformation during rolling leads to new β orientations being generated that are able to out-compete growth from the residual β upon reheating

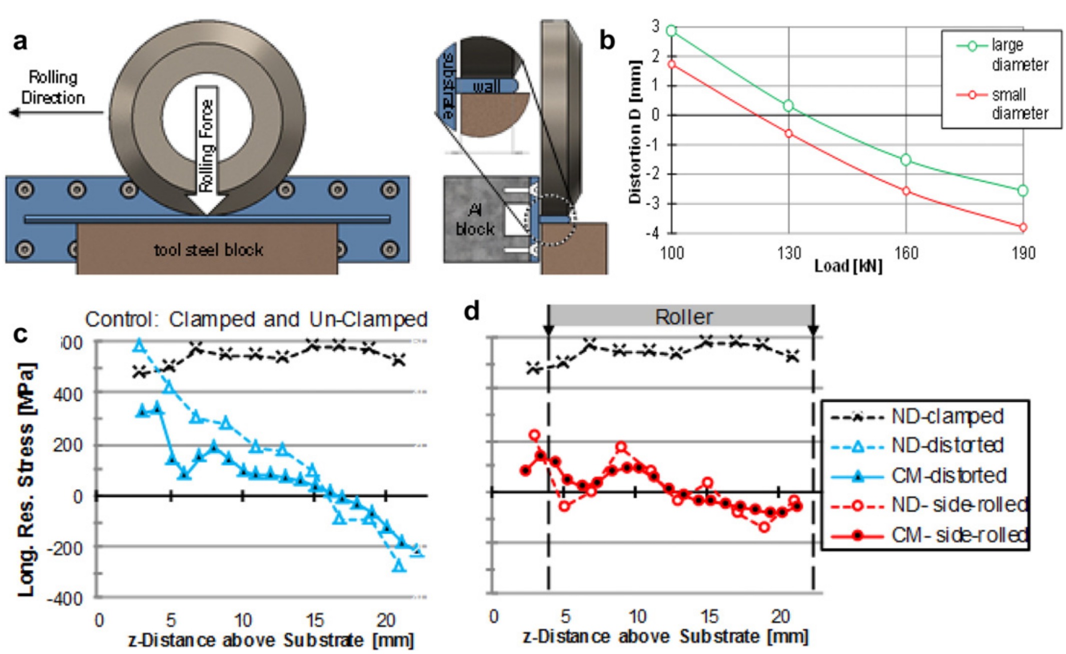

Fig. 3. (a) Schematic diagram of side rolling, (b) reductions in the out-of-plane distortion as a function of rolling load; residual stresses (c) before and (d) after rolling as measured with the neutron and contour methods, with an applied load of 130 kN and a150 mm roller. Results are reported in Hönnige et al. [11].

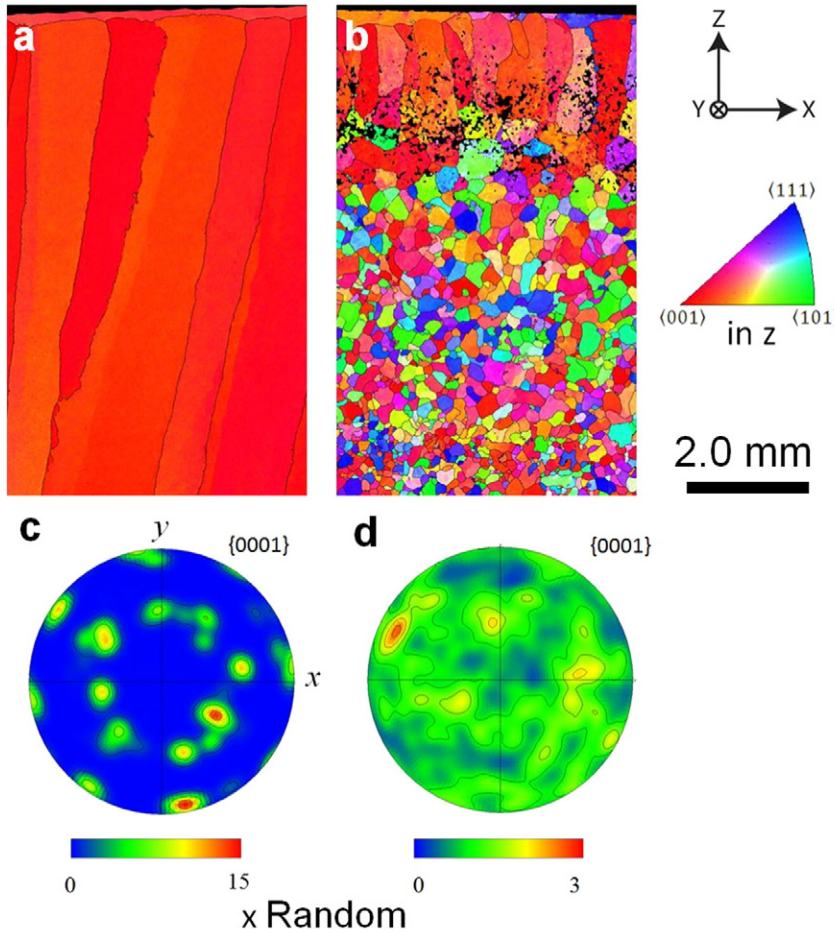

Fig. 4. IPF β orientation maps of WAAM Ti-6Al-4V builds without (a), and with (b), cold rolling applied between every deposited layer. (c) and (d) give the respective room temperature α textures of the regions.
Adapted from [5].

above the β transus, and prevent re-establishment of the previous high temperature (columnar) microstructure. The origin of these new β orientations will be the subject of a future publication, and have been identified as initiating from twinned α colonies in the deformed microstructure, and also as a result of deformation accommodation mechanisms in the retained β phase, related to the fine transformation structure developed in the WAAM process.

The application of rolling to aluminium alloys does not provide the same level of grain refinement because it already has a much finer non-columnar grain structure [14]. Microstructures of rolled single bead wide WAAM walls produced with an AlCu6.3 (2219) alloy were studied by Gu et al. [14]. After rolling, as expected, the grain structure was elongated along the short-transverse direction and became gradually finer with increased rolling loads. The strain was around 14%, 31% and 45% under the loads of 15 kN, 30 kN and 45 kN respectively. These loads reduced the average grain size from 26.7 μm to 12.8 μm for the 15 kN rolling load, and 8.7 μm and 7.7 μm with 30 kN and 45 kN rolling loads, respectively. The eutectic particles (α-Al + θ

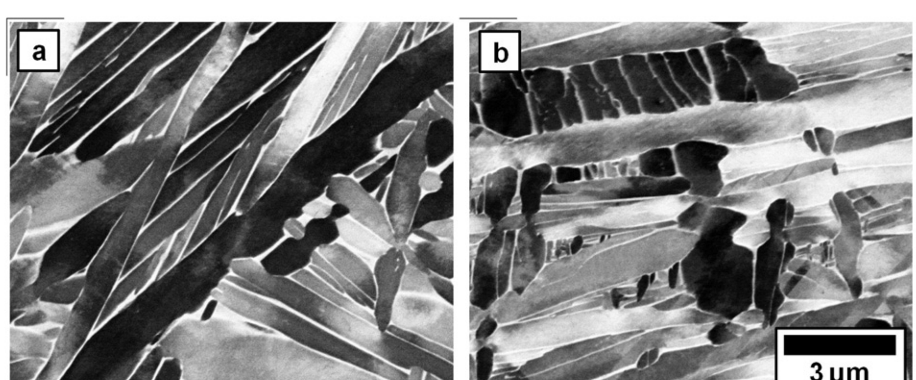

Fig. 5. Scanning electron microscope images of WAAM Ti-6Al-4V which is (a) undeformed and (b) interpass rolled with a contoured roller and a 75 kN rolling load. Note that rolling was the final processing step.

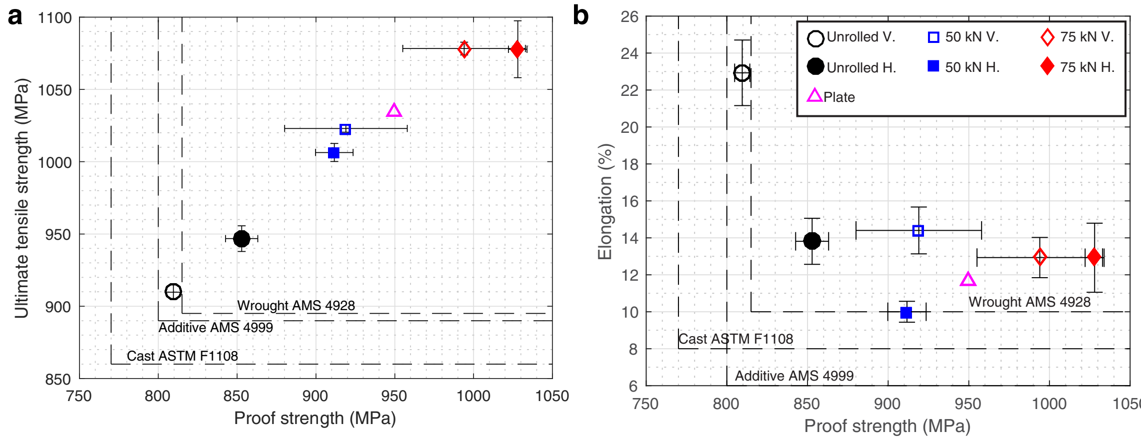

Fig. 6. Direction-specific tensile properties of Ti-6Al-4V deposited by WAAM: (a) ultimate tensile strength vs proof strength and (b) elongation vs proof strength. Error bars show 95% confidence intervals and the property requirements from AMS and ASTM standards are shown with the dashed lines in the figure. V = vertical direction and H = horizontal direction.

phases) produced by microsegregation during solidification were also fractured into smaller pieces, which were distributed in the rolling direction. Higher rolling loads thus resulted in smaller second phase particles within the as-deposited builds. Rolling was also found to induce a high dislocation density, which recovered into a fine cell structure, resulting in low misorientation sub-grains forming during the subsequent deposition pass.

Finally, high levels of grain refinement have also been reported when applying in-situ rolling directly behind the melt pool while depositing 316L stainless steel experimentally by Xie et al. [8] and in detail by Zhou et al. [4] who used a 2-dimensional cellular automata model to predict the grain structure developed. The model was applied to 316L stainless steel where the kinetics of recrystallization are well understood. This work accurately predicted both the columnar solidification microstructure as well as the size of the region refined by rolling, which grew in size with increasing rolling load.

4. Material properties

Extensive mechanical testing of rolled WAAM samples has been carried out by the Cranfield group to determine the effect on mechanical properties. The tensile properties of Ti6-Al-4V single pass wide parallel walls, determined by Martina [7], are summarised in Fig. 6, for both the horizontal (wall) and vertical (build) directions. The anisotropy normally present in the unrolled conventional AM material is clearly evident in Fig. 5, particularly in terms of the ductility which is significantly worse in the horizontal direction. This undesirable anisotropy was virtually eliminated by the application of in-process rolling. Both the ultimate tensile and proof strengths were also improved compared to for the unrolled material, and a greater improvement was seen with greater rolling loads. Overall, for the rolling loads studied, which gave average plastic deformations in the range 8% (50 kN) to 18% (75 kN), superior properties were measured than required by various standards for standard wrought material (see Fig. 6).

These benefits to the mechanical properties from interpass rolling are clearly related to the greatly improved prior β microstructure and texture seen in Fig. 2. Although both the rolled and un-rolled materials have a similar transformation microstructure, the coarse prior β grain structure in the conventional material contributes most significantly to the anisotropy in ductility. This is because the long parallel prior β grain boundaries, aligned in the vertical direction, seen in a conventional WAAM deposit are associated with both a thin layer of grain boundary α and a β grain boundary colony α region, which is softer than the Widmanstätten matrix and concentrates slip, leading to premature failure transverse to the build direction [15]. The fine equiaxed prior β structure produced by rolling thus eliminates this problem. The smaller increase in yield strength achieved by rolling is less easily explained as the transformation structure was comparable in both cases owing to rolling not greatly affecting the cooling rate through the β transus. This effect is also probably primarily texture related, although there may be some subtle differences in the homogeneity of the transformation structure associated with the finer parent β grain size, yet to be determined.

A critical property for aerospace requirements is fatigue. Fig. 7 shows high cycle fatigue results from specimens that were tested according to BS EN BS EN 6072:2010 using the T-Type sample with a hole with a stress concentration (Kt) of 2.3 and an R value of 0.1. The samples were stress relieved at 680 °C prior to testing and are compared against Airbus standards for forged and cast material. The rolled WAAM material has a fatigue strength that is almost twice that required by the standard. Wang et al. [16] demonstrated that even without rolling WAAM Ti-6Al-4V can have superior fatigue life to wrought material, provided the deposited material is free from defects such as gas pores [16]. Overall, the results compare very favourably with high cycle fatigue results for Ti-6Al-4V reported in the literature by Nalla et al. [17] (for both lamellar and bimodal microstructures) and Chen et al. [18] (cast - βeta annealed) for *cylindrical* specimens with an R value of 0.1. The results for the WAAM material were superior to those for the cast material and a little lower than those for the lamellar and bimodal material, however the WAAM material was tested with samples that had a stress concentrating feature (hole) that lowered the fatigue life while those in the literature did not.

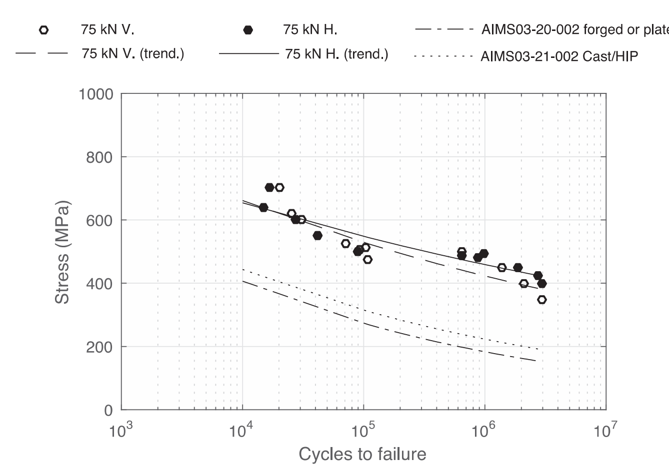

Fig. 7. High cycle fatigue life of Ti-6Al-4V deposited by WAAM and treated with high-pressure interpass rolling.

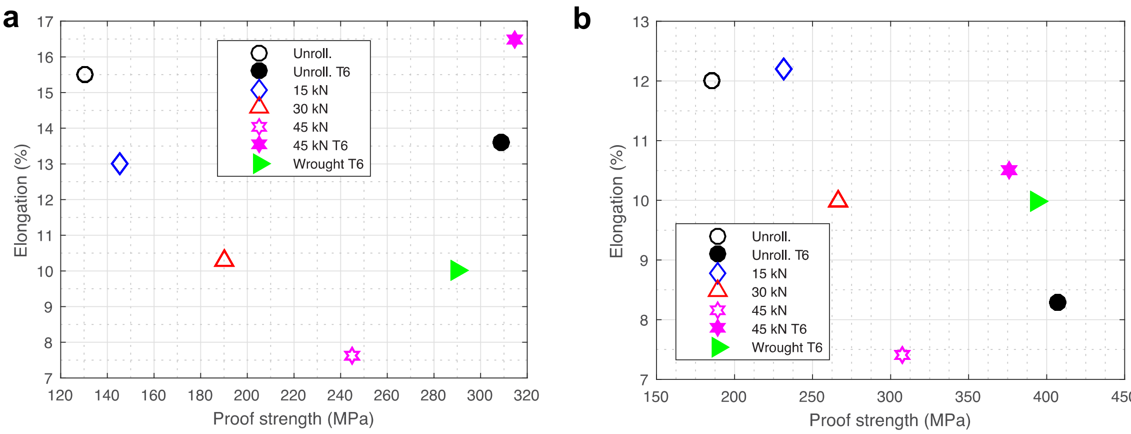

Fig. 8. Elongation vs. proof strength for (a) 2219 and (b) 2024 WAAM aluminium alloys.

Initiation determines the fatigue life in high cycle fatigue. Zuo et al. [19] reported that with a Widmanstätten basket-weave microstructure that is found in the rolled WAAM walls, fatigue cracks initiate *internally* at alpha-beta interfaces associated with lamellar colonies at prior β grain boundaries. In titanium alloys a coarse distribution of texture can also have an effect on high cycle fatigue performance, particular where it is associated with the formation of macro zones [20] although the effect of a randomised texture was not studied. Therefore, it is likely that it is the combination of a higher proof strength, fine Widmanstätten basket-weave microstructure and more isotropic texture with a small prior β grain structure, provided by rolling, produced the excellent high cycle fatigue properties. Finally, rolling may also reduce porosity (as demonstrated in the next section) which can reduce fatigue life [16].

There are also mechanical property benefits from applying in-process rolling to aluminium alloys deposited by the WAAM process. The tensile properties of rolled 2219 material were investigated by Gu et al. [14] who reported an improvement in strength, which is summarised in Fig. 8(a). The material's yield and tensile strength increased following the application of rolling, when compared to the as-deposited material, however, this was at the expense of ductility. As reported above, this improved strength is probably from the cold work introduced and fine sub-grains formed during rolling the WAAM material. For example, after a full T6 heat treatment, involving solution treatment where the rolled material recrystallised, the strength of both the unrolled and rolled WAAM samples was virtually identical, although the elongation of the rolled material was superior. This may be due to lower porosity levels (discussed below) and the break-up of primary particles in the rolled deposits, as well as the smaller grain size of this material.

The results from recent studies on 2024 aluminium alloy are shown in Fig. 8(b) which has superior strength to 2219, making it more attractive for aerospace applications. Similar characteristics were observed with this alloy. As deposited, this material had a poor ductility in the vertical direction in the T6 condition and interpass rolling was able to improve the elongation significantly to over 10%.

Material properties for in-situ WAAM rolling of 304 stainless steel are reported in Xie et al. [8]. Although there was a significant refinement in the microstructure, the improvement in tensile properties seen for this material was relatively small – generally less than 10%.

5. Porosity reduction

Porosity is an endemic problem in aluminium alloys in processes that cause melting due to a large difference in the solubility of hydrogen in liquid and solid aluminium. In additively manufactured parts, the porosity often occurs in bands associated with each deposited layer [21], and can have a detrimental effect on mechanical properties – particularly in the vertical direction where the load is perpendicular to the bands. Porosity can to some extent be reduced by optimising the process parameters, as investigated by Cong et al. for WAAM [21] and selective laser melting by Aboulkhair et al. [22]. Although higher density AM aluminium deposits could be achieved, elimination of porosity is highly dependent on the feedstock material quality, which is difficult to control.

During conventional rolling of aluminium alloys, pore closure has been reported by Toda et al. [23–25]. However, these studies were performed on metal ingots and plates rather than AM parts. Similarly, when applying rolling to the WAAM of aluminium alloys 2219 and 5087 between each deposited layer, a large reduction in porosity has been observed [26]; as shown in Table 1, where the total number, mean diameter, area percentage and sphericity of the pores were all reduced with increasing rolling load, indicating that pores for both alloys were gradually flattened to oblate spheroids before closure. Images showing the porosity reduction after rolling are provided in Figs. 3 and 4 of Gu et al. [26]. This reduction of porosity defects is one reason for the ductility improvement of rolled WAAM aluminium alloys reported in the previous section.

It has been suggested that for hydrogen porosity rolling can lead to significant pore healing because the hydrogen within the pores prevents internal surface oxidation [25]. The high density of dislocations

Table 1
Analysis of pores for WAAM AlCu6.3 and AlMg4.5 alloys.

	Alloy	As-deposited	15 kN rolled	30 kN rolled	45 kN rolled
Number of pores (in a total area of 120 mm2)	AlCu6.3	614	192	5	Pores were eliminated to a level below the resolution of optical microscopy.
	AlMg4.5	454	336	11	
Mean diameter (μm)	AlCu6.3	13.5	12.5	8.8	
	AlMg4.5	25.1	13	9.6	
Area percentage (%)	AlCu6.3	0.176	0.029	0.005	
	AlMg4.5	0.232	0.061	0.007	
Mean sphericity	AlCu6.3	0.74	0.67	0.37	
	AlMg4.5	0.74	0.63	0.42	

induced by cold working can also act as preferential sites for atomic hydrogen absorption. In addition, Toda et al. [23] have suggested that these dislocations could act as 'pipes' for the hydrogen which allow it to diffuse to the surface. Irrespective of the mechanism, the reduction of porosity is an important finding that could facilitate industrial implementation of WAAM for aluminium.

6. Roller design and methods

To date, most articles have investigated the application of rolling in AM to single pass walls and have used rollers that are either flat or profiled [2,3,6]. Work by Martina et al. [6] has demonstrated that similar levels of grain refinement can be achieved with both profiles, although the extremities of the wall were less refined with the flat roller. In addition, recent work from Huazhong University by Xie et al. [8] has demonstrated the application of pinch rollers (Fig. 1(c)) operating in tandem just ahead of a flat roller, termed by this group 'a miniature metamorphic rolling mechanism'. By dynamically controlling the rollers such an approach has the advantage of providing highly accurate and flexible control of the final part geometry.

More recent investigations by Colegrove et al. [27] have demonstrated that achieving grain refinement in thick titanium walls, with standard roller profiles, is difficult because of the problem of inducing strain in the material due to the greater lateral restraint. Therefore, an inverted roller profile (Fig. 1(d)) was developed to increase the deformation underneath the surface of the material and this was able to provide good levels of grain refinement, although several passes were required to cover the width of the wall (a modified roller with several inverted profiles may avoid this issue). Finally, this roller profile has also been successfully applied to intersecting features where it is also difficult to induce sufficient strain due to the highly restrained geometry.

7. Sliding severe plastic deformation

Book and Sangid [28] have investigated the use of sliding severe plastic deformation (SPD) with direct metal laser sintering AM. The technique has some similarities with machining, but uses a tool with a large negative angle that deforms rather than cuts the surface. Like rolling, the technique was applied between passes and resulted in significant refinements in the grain size, which provided greater strain homogeneity when the part was subsequently loaded. However the SPD process causes a large shear force that resulted in surface cracking: the authors thus concluded that rolling methods may be preferable.

8. Future direction

Application of deformation methods, and rolling in particular, to additively manufactured components is a field still in its infancy. The substantial improvement in mechanical properties that can be achieved with the process suggests that there is likely to be a promising future. One of the significant questions is whether the added cost of implementing the technique can justify the benefits. A manufacturing cell based on the technology could have two work-stations running in parallel manufacturing two parts at the same time. Therefore, while one part is deposited, the second could be deformed/rolled and then the two parts interchanged.

Another question is whether rolling is the most effective deformation process, or whether alternative techniques, such as peening, could be more effective. In a preliminary study by Donoghue et al. [13] ultrasonic peening was found to refine the microstructure when applied to laser blown powder AM, however the amount of refinement was less than that obtained with rolling methods and the microstructure was not as homogeneous. This occurred because in peening, the majority of the deformed material is remelted by the next deposition pass, as the strain introduced is localised near the surface. This technique does however avoid the high loads required by vertical rolling, making implementation easier. Other peening methods (e.g. laser, hammer) could also be beneficial, but will also have difficulty providing bulk deformation to a sufficient depth to avoid being removed by re-melting.

Although side rolling is rather impractical in its current form because of the need to unclamp and rotate the specimen, pinch rolling where a wall is rolled with two opposed rollers (Fig. 1(c)) could be implemented relatively easily with a similar effect. In addition, since the loads are reacted using a yoke between the two rollers, a large external load is not required so this method could be applied robotically, although both techniques are not suited to parts with intersecting features and would be limited to straight walls or revolved sections.

While there have been several investigations into the residual stress generation in straight single pass walls, there is currently little understanding of the behaviour of more complex parts, or even simple intersections such as a tee or cruciform. This problem applies not only to rolled AM parts but AM parts in general. Residual stress generation is likely to be more complex in such situations due to the multi-axial stress state present at intersections. Furthermore, effective rolling of intersecting features and wide walls has only just been demonstrated and much work is required to optimise rolling shapes and loads, understand the associated microstructural refinement and residual stress and distortion generation.

The recent article from Zhou et al. [4] on the microstructural modelling of in-situ rolling, or HDMR, has demonstrated the usefulness of models that predict the thermal history, deformation and microstructure for the combined deposition/rolling process. These models will improve our understanding of the underlying physics and could enable the optimisation of more effective roller systems.

At present, no models have been developed to predict the grain refinement in titanium which is likely to be one of the main applications. Nevertheless, in recent investigations [5] the reasons for the refinement are beginning to be understood. Microstructural models are required to predict the amount of refinement in the prior β and α lamellae size, from the prior microstructure, amount of deformation and the thermal cycle. Given the wide use of titanium and the limited microstructural models available, the difficulty of this task should not be underestimated.

Thermal and mechanical models that predict the residual stress and distortion from the combined deposition and rolling process would also provide a valuable insight into the process and could facilitate the design of rollers and development of rolling techniques. However, the multiple deposition and rolling stages involved result in models with very long computational times unless computationally efficient methods are implemented [29–31].

Finally, the in-situ (HDMR) method provides significant grain refinement and has the advantage of being applied simultaneously with material addition, avoiding the need for the part to cool down between passes. Application to titanium alloys could be very beneficial and would be well-suited to parts without intersecting features.

One of the crucial areas for AM is the generation of a tool path from a CAD model of a part. This is reasonably well developed for laser selective melting and laser metal deposition systems where there are a large number of commercial systems available. The problem is more complex for WAAM where it is necessary to minimise the number of times the deposition process is turned off and on to avoid defects. In addition, it is important to carefully consider how intersecting features are produced where defects are more likely. A few methods for solving this problem have been proposed in the literature such as polygon subdivision by Dwivedi and Kovacevic [32] and adaptive medial axis transformation by Ding et al. [33]. At Cranfield University we are developing a library of deposition strategies that are suited to different part geometries and materials which avoid the production of defects. We are in the process of automating the generation of the tool paths from the part geometry using this knowledge database.

9. Conclusions

In this viewpoint article we have summarised the latest state-of-the-art in applying bulk in-process deformation techniques to large scale AM. The main findings are:

- Rolling can be applied either independently interpass at room temperature or immediately following the deposition head. Both methods of application lead to a significant refinement in the microstructure.
- When applied vertically, rolling processes provide limited improvement to the residual stress and distortion of the deposited part, since much of the deformation is induced lateral to the direction of deposition. Greater residual stress reductions can be achieved by applying rolling methods that prevent this lateral deformation – by using either a slotted roller or side rolling.
- For titanium there are significant improvements to both the microstructure and mechanical properties as a consequence of interpass rolling. A high level of refinement in the prior β grain structure can be achieved for moderate applied strains, which results in improved and isotropic properties. Recent fatigue results are particularly promising and the material has significantly better properties than those required by current standards.
- There are also benefits when applying rolling to aluminium where porosity is eliminated. In addition, interpass rolling improved the ductility of 2024 in the vertical direction – removing one of the main barriers to WAAM deposition of this material.
- Future work will apply the technology to new geometries and materials as well as fundamental studies that improve our understanding of the mechanisms and kinetics of grain refinement.

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References

[1] H.E. Coules, P. Colegrove, L.D. Cozzolino, S.W. Wen, J.F. Kelleher, Sci. Technol. Weld. Join. 18 (2012) 84–90.
[2] P.A. Colegrove, H.E. Coules, J. Fairman, F. Martina, T. Kashoob, H. Mamash, L.D. Cozzolino, J. Mater. Process. Technol. 213 (2013) 1782–1791.
[3] H. Zhang, X. Wang, G. Wang, Y. Zhang, Rapid Prototyp. J. 19 (2013) 387–394.
[4] X. Zhou, H. Zhang, G. Wang, X. Bai, Y. Fu, J. Zhao, J. Mater. Sci. 51 (2016) 6735–6749.
[5] J. Donoghue, A.A. Antonysamy, F. Martina, P.A. Colegrove, S.W. Williams, P.B. Prangnell, Mater. Charact. (2016).
[6] F. Martina, P.A. Colegrove, S.W. Williams, J. Meyer, Metall. Mater. Trans. A 46 (2015) 6103–6118.
[7] F. Martina, Investigation of Methods to Manipulate Geometry, Microstructure and Mechanical Properties in Titanium Large Scale Wire + Arc Additive Manufacturing, Cranfield University, 2014.
[8] Y. Xie, H. Zhang, F. Zhou, J. Manuf. Sci. Eng. 138 (2015).
[9] F. Martina, M.J. Roy, B.A. Szost, S. Terzi, P.A. Colegrove, S.W. Williams, P.J. Withers, J. Meyer, M. Hoffmann, Mater. Sci. Technol. 32 (14) (2016) 1439–1448.
[10] D. Ding, Z. Pan, D. Cuiuri, H. Li, Int. J. Adv. Manuf. Technol. 81 (2015) 465–481.
[11] J.R. Hönnige, S. Williams, M.J. Roy, P. Colegrove, S. Ganguly, 10th Int. Conf. Residual Stress., Sydney, 2016.
[12] A.A. Antonysamy, J. Meyer, P.B. Prangnell, Mater. Charact. 8 (2013) 153–168.
[13] J. Donoghue, J. Sidhu, A. Wescott, P. Prangnell, TMS2015 Suppl. Proc. 437–444 (2015).
[14] J. Gu, J. Ding, S.W. Williams, H. Gu, J. Bai, Y. Zhai, P. Ma, Mater. Sci. Eng. A 651 (2016) 18–26.
[15] G. Lütjering, Mater. Sci. Eng. A 243 (1998) 32–45.
[16] F. Wang, S. Williams, P. Colegrove, A.A. Antonysamy, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 44 (2013) 968–977.
[17] R.K. Nalla, B.L. Boyce, J.P. Campbell, J.O. Peters, R.O. Ritchie, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. (2002) 899–918.
[18] W. Chen, C.J. Boehlert, Mater. Sci. Eng. A 494 (2008) 132–138.
[19] J.H. Zuo, Z.G. Wang, E.H. Han, Mater. Sci. Eng. A 473 (2008) 147–152.
[20] I. Bantounas, T.C. Lindley, D. Rugg, D. Dye, Acta Mater. 55 (2007) 5655–5665.
[21] B. Cong, J. Ding, S. Williams, Int. J. Adv. Manuf. Technol. 76 (2015) 1593–1606.
[22] N.T. Aboulkhair, N.M. Everitt, I. Ashcroft, C. Tuck, Addit. Manuf. 1 (2014) 77–86.
[23] H. Toda, K. Minami, K. Koyama, K. Ichitani, M. Kobayashi, K. Uesugi, Y. Suzuki, Acta Mater. 57 (2009) 4391–4403.
[24] H. Toda, T. Hidaka, M. Kobayashi, K. Uesugi, A. Takeuchi, K. Horikawa, Acta Mater. 57 (2009) 2277–2290.
[25] H. Toda, T. Yamaguchi, M. Nakazawa, Y. Aoki, K. Uesugi, Y. Suzuki, M. Kobayashi, Mater. Trans. 51 (2010) 1288–1295.
[26] J. Gu, J. Ding, S.W. Williams, H. Gu, P. Ma, Y. Zhai, J. Mater. Process. Technol. 230 (2016) 26–34.
[27] P.A. Colegrove, A.R. McAndrew, J. Ding, F. Martina, P. Kurzynski, S. Williams, 10th Int. Conf. Trends Weld. Res., Tokyo, 2016.
[28] T.A. Book, M.D. Sangid, JOM 68 (2016) 1780–1792.
[29] J. Ding, P. Colegrove, J. Mehnen, S. Williams, F. Wang, P.S. Almeida, Int. J. Adv. Manuf. Technol. 1–10 (2013).
[30] J. Ding, P. Colegrove, J. Mehnen, S. Ganguly, P.M.S. Almeida, F. Wang, S. Williams, Comput. Mater. Sci. 50 (2011) 3315–3322.
[31] N. Patil, D. Pal, H. Khalid Rafi, K. Zeng, A. Moreland, A. Hicks, D. Beeler, B. Stucker, J. Manuf. Sci. Eng. 137 (2015) 41001.
[32] R. Dwivedi, R. Kovacevic, J. Manuf. Syst. 23 (2004) 278–291.
[33] D. Ding, Z. Pan, D. Cuiuri, H. Li, S. van Duin, N. Larkin, Robot. Comput. Integr. Manuf. 39 (2016) 32–42.