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Viewpoint article

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

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A B S T R A C T

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).

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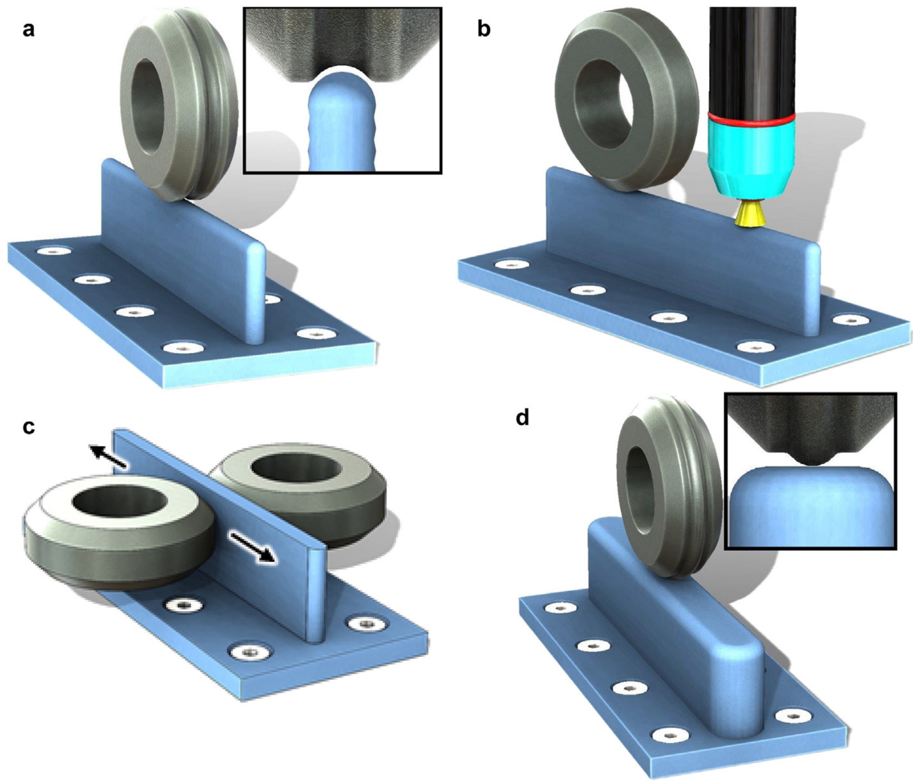

Fig. 1. Schematic diagram of the main rolling methods: (a) vertical with a profiled roller; (b) in-situ rolling; (c) pinch rolling (d) rolling with an inverted profiled roller for thick sections and intersections.

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

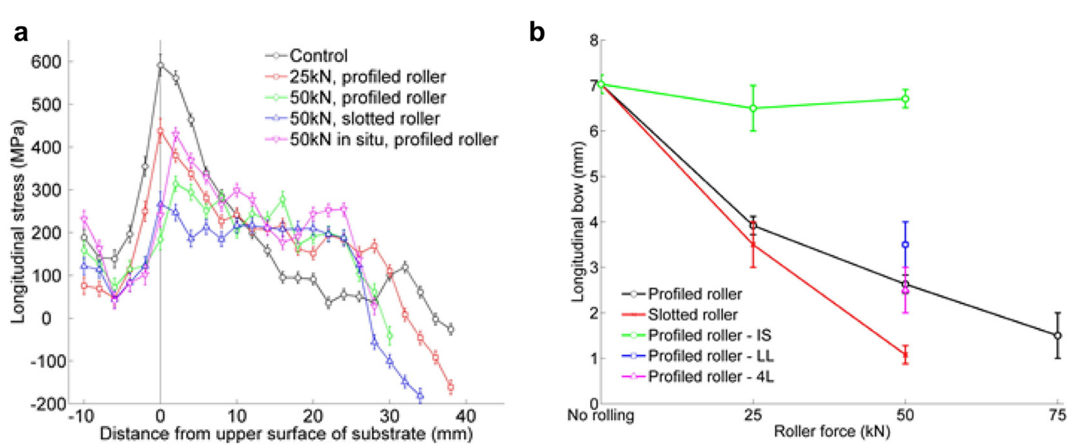

Fig. 2. (a) Residual stresses measured in unclamped steel specimens after rolling with profiled and slotted rollers at different loads; (b) corresponding distortion measurements at different loads. Note IS = in-situ, LL = rolling of last layer only, and 4L = rolling every fourth layer. Full results are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

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