

# RESIDUAL STRESS REDUCTION IN HIGH PRESSURE INTERPASS ROLLED WIRE+ARC ADDITIVE MANUFACTURING TI-6AL-4V COMPONENTS

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## Abstract

Wire+arc additive manufacturing (WAAM) components are characterised by high residual stress due to the many consecutive deposition passes. Residual stress results in distortion once the part is unclamped. High-pressure rolling was investigated as a way to address this issue in Ti-6Al-4V linear parts. Rolling loads of 50 kN and 75 kN were investigated. Residual stress measurements, performed with the contour method, showed rolling was successful in reducing residual stress substantially, especially at the interface between the part and the baseplate. High-pressure interpass rolling is likely to facilitate the implementation of WAAM for the manufacture of structural aerospace components.

## 1 Introduction

Wire+arc additive manufacturing (WAAM) is an Additive manufacturing (AM) process based on arc-welding techniques, such as metal inert gas welding (Almeida and Williams, 2010), Tungsten inert gas (TIG) welding (Wang et al., 2013), or plasma arc welding (Martina et al., 2012).

Residual stress and distortion are some of the issues affecting WAAM (Ding et al., 2011). Various techniques have been developed to address them, including mechanical tensioning and peening methods. Mechanical tensioning can be either global or local. High-pressure rolling (Altenkirch et al., 2009) is a local tensioning method which is easy to implement and does not require expensive equipment; moreover, it has a large depth of influence in the material compared to peening, whose influence is limited to 1 mm to 2 mm. Initially developed for friction stir weldings (Altenkirch et al., 2009), and steel thin-sheet welds (Coules et al., 2012), it was recently applied to WAAM steel structures by Colegrove et al. (2013). They found that interpass rolling reduced distortion and residual stress, and refined the grain structure. Martina et al. (2013) investigated interpass rolling of Ti-6Al-4V WAAM linear structures, and demonstrated that rolling not only reduced prior  $\beta$  grain size and  $\alpha$  laths thickness, but also resulted in improved isotropic mechanical properties, which were better than the wrought material.

In this paper, residual stress were characterised in as-deposited and interpass rolled Ti-6Al-4V WAAM linear deposits, using the contour method (Prime, 2001).

## 2 Experimental method

A Lincoln Electric Invertec V310-T TIG power supply was used to deposit titanium wire onto a  $250 \times 60 \times 6 \text{ mm}^3$  Ti-6Al-4V substrate. The TIG torch was attached to a linear manipulator which also provided the motion and the load to perform the rolling pass (Fig. 1 — the reference system is provided in this figure). Each linear deposit began and ended on the edges of the substrate, and was made of 40 layers. The wire was fed in front of the torch as shown in Fig. 1. Rolling was interpass, i.e. each layer was rolled after the deposit had cooled to room temperature. The roller had a profile with a 3.6 mm machined radius. For the deposition and rolling parameters please refer to Table 1. Two rolling loads were investigated, 50 kN and 75 kN.

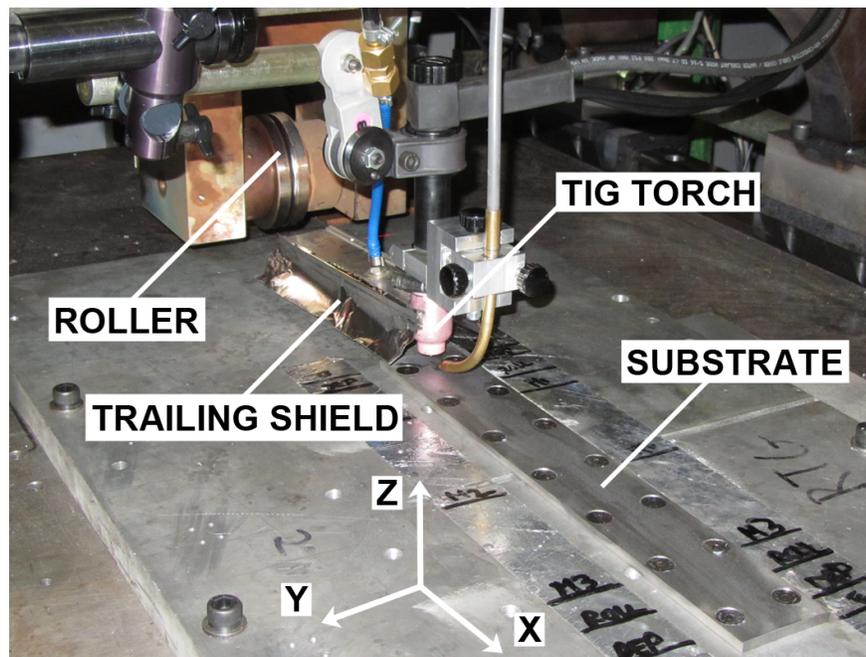


Figure 1: Experimental setup for rolling investigation.

Table 1: Deposition and rolling parameters

Wire feed speed	$1.6 \text{ m min}^{-1}$
Travel speed	$4.5 \text{ mm s}^{-1}$
Peak current	150 A
Background current	70 A
Average current	110 A
Pulse duration	0.05 s
Frequency	10 Hz
Rolling speed	$3 \text{ mm s}^{-1}$

### 2.1 Contour method

The contour method is a destructive residual stress measurement technique which relies on elastic superposition. With this method, components are carefully cut as to not introduce any

further residual stress, and the distortion of the resulting cut faces due to residual stress is measured relative to a perfectly flat plane. This distortion is then employed as boundary conditions in a linear-elastic finite element analysis to resolve residual stresses.

Specimens in this study were cut via wire electric discharge machining starting from the top of the deposit and travelling through the baseplate last, parallel to the  $Y$  axis (Fig. 1). The resulting cut faces were then measured using a NanoFocus  $\mu$ Scan laser profilometer providing two independent point clouds with  $YZ$  resolutions of  $30\ \mu\text{m}$  by  $30\ \mu\text{m}$ . These two point clouds were aligned and averaged. This single point cloud was fitted with a series of splines such that any  $YZ$  location within the boundary of the component could be interpolated to provide an  $X$  value. This numerical surface had a fitting error of  $15.58\ \mu\text{m}$  with a standard deviation of  $1.23\ \mu\text{m}$ , which is within the error of the laser profilometre.

The  $XY$  coordinates of the part's periphery was then used to generate a 3D meshed component comprising  $\sim 83000$  nodes and  $\sim 19000$ , 20-node, reduced integration quadrilateral elements. Elastic properties for Ti-6Al-4V (Young's modulus equal to  $113.8\ \text{GPa}$ , and Poisson ratio equal to  $0.342$ ) were assigned to the material. Translation boundary conditions in the  $X$  direction were applied directly to corresponding surface nodes, and rigid body motion was suppressed by appropriate boundary conditions applied to single nodes on the bottom of the baseplate. The  $X$  direction translation boundary conditions were interpolated from the numerical surface described above. This analysis was then solved implicitly via ABAQUS Standard.

Results from the finite element analysis were then tabulated to provide RS values along the centreline of the part.

### 3 Results

Fig. 2 shows a comparison of the residual stress in the longitudinal ( $X$ ) direction for control and rolled specimens. The control specimen showed tensile stress ( $500\ \text{MPa}$ ) concentrated above the interface between the part and the baseplate. Residual stress decreased towards the top of the wall; here stresses became compressive, with a minimum value of  $-250\ \text{MPa}$ . The  $75\ \text{kN}$  specimen showed a lower residual stress. At the interface between the part and the baseplate the stresses in the specimen rolled at  $75\ \text{kN}$  were  $300\ \text{MPa}$  less than the control specimen.

The rolled specimens exhibited lower tensile stresses (between  $100\ \text{MPa}$  and  $200\ \text{MPa}$ ) across the wall and highly compressive stresses were produced in the top layers, with values of  $-400\ \text{MPa}$  and  $-500\ \text{MPa}$  for the  $50\ \text{kN}$  and  $75\ \text{kN}$  specimens, respectively. The area showing compressive stress (shown in Fig. 2) could represent the depth of the strain induced by the last rolling pass.

During part building there was a competition between the production of tensile residual stress by each deposited layer, and the compressive stress introduced by each subsequent rolling pass. The fact that distortion was not eliminated completely suggests that the depth affected by welding stress generated during the deposition of a layer was larger than the one influenced by each rolling pass.

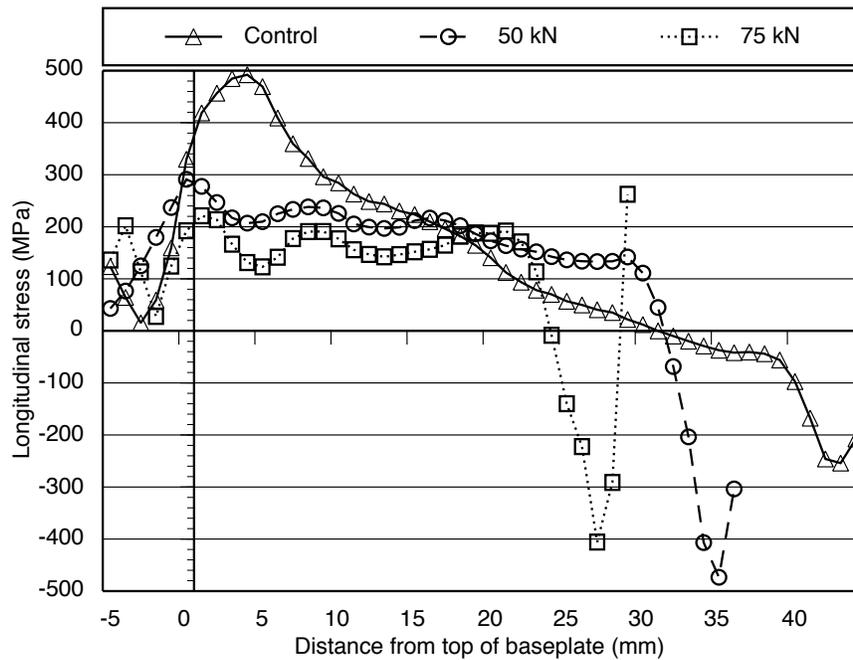


Figure 2: Longitudinal residual stress measured by contour method.

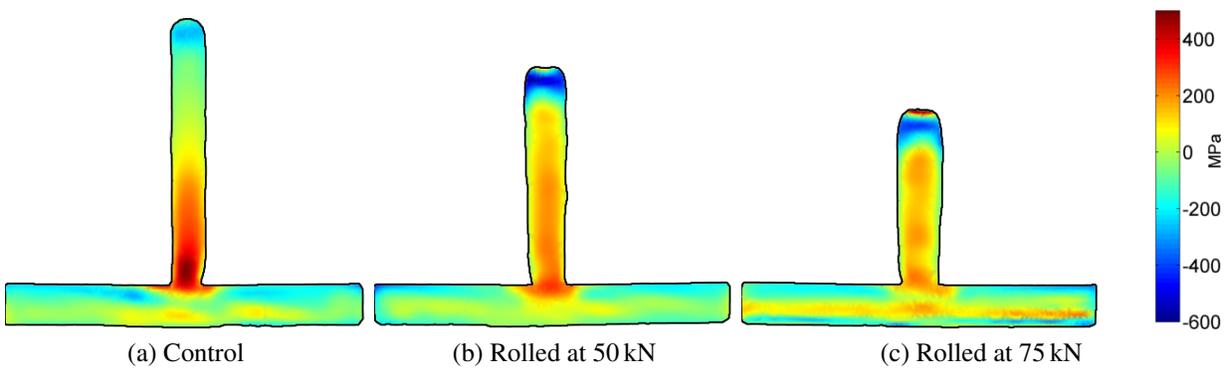


Figure 3: Contour maps of residual stress. Please note the scale is the same. The difference in the height of the components is due to the plastic deformation induced by rolling.

The contour method enabled the measurement of stress much closer to the surface than diffraction methods. Consequently it was possible to identify and measure the tensile stress in the region at the top of the wall. This tensile stress has been reported in other publications investigating the effect of rolling and was produced by the friction between the roller and the material (Bijak-Zochowski and Marek, 1997). This resulted in a larger strain induced within the bulk of the material than at the surface.

Fig. 3 shows contour maps of residual stress in as-deposited and rolled specimens. The stresses at the surface are slightly more compressive than those within the material.

#### **4 Summary and conclusions**

This research has identified the highest residual stress in Ti-6Al-4V WAAM specimens are found at the interface between the substrate and the deposit. Rolling reduced these stresses but did not eliminate them completely; consequently rolled parts still demonstrated distortion. Future work is required to understand how the residual stresses are reduced and to mitigate distortion.

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