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Influence of macrosegregation on solidification cracking in laser clad ultra-high strength steels

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ABSTRACT

Alloy selection is critical for the performance of aerospace components repaired through laser cladding, as unsuitable combinations of clad and substrate materials can lead to defects during deposition. Different combinations of laser clad ultra-high strength steels have been studied to examine the effect of material composition on clad quality. Clad/substrate combinations of Aermet®100/300M, Aermet®100/4340, and 4340/300M were trialled using a range of processing parameters. While no defects occurred in the 4340/300M samples, solidification cracking was observed in the Aermet®100 multi-track clad samples, especially on 300M substrates. The cracking originates from macrosegregation trails caused by differences in melting temperature between clad and substrate. These trails interfere with liquid feeding beneath them when the substrate has a higher liquidus temperature, with entrapped liquid leading to short solidification cracks. A second larger form of solidification cracking was found in Aermet®100/300M due to Aermet®100 solidifying faster in the late stages of solidification, as this can entrap liquid in the inter-dendritic regions leading to cracking. Both forms of cracking can be avoided by increasing the laser interaction time during cladding, as this slows the solidification process to allow for more complete mixing and liquid feeding.

1. Introduction

300M is an ultra-high strength low alloy steel that finds wide use in aircraft landing gear and other critical airframe components [1–3]. The composition of 300M is a modification of the AISI 4340 alloy with additional silicon to allow the alloy to be hardened well outside of the brittle tempering range, while an addition of vanadium is used to restrict the growth of austenite grains during austenitising [3,4]. Given the high stresses at which 300M components operate, they are particularly sensitive to damage caused by fatigue, corrosion, and impact from foreign objects [5–7]. The discovery of any type of crack often requires these components to be replaced, often at great expense given the strict quality standards for aerospace applications. This problem is further complicated by the fact that many aircraft are operated far beyond their intended design lives [8], as not only are the components of advanced age and wear, but replacement parts become increasingly scarce. The existing solution to this problem is to use a grind-out technique to remove any cracking; however, this can only be done if the component remains within tight dimensional limits [9]. As such, there is a need to develop a more applicable and sustainable approach for the repair of these components.

Laser cladding has emerged as a novel repair technique for aerospace components as the damaged area removed by grind-out can be replaced by freshly deposited material, thus restoring the component to its original form [8–10]. Materials produced by laser deposition have already drawn considerable attention for aerospace applications, particularly in steels [11–13], Ni-based superalloys [14–18] and Ti-6Al-4V [19–21]. Applying the same process for repair applications is highly advantageous, as the low levels of dilution, minimal distortion, and small heat affected zones produced by laser cladding provide minimal changes to the underlying material [22–24]. While little work has focused on the laser clad repair of 300M, there have been investigations into other ultra-high strength steels such as 4340 [9] and Aermet®100 [10,25], which are also used in landing gear components. For Aermet®100, laser cladding has proven effective at extending the fatigue life of a damaged component [25]. Additionally, the repaired material has been shown to have the same crack growth characteristics as a conventionally produced sample [10]. For 4340, laser clad repair

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Table 1
Chemical composition for clad and substrate materials (wt%).

	Fe	C	Co	Cr	Mn	Mo	Ni	P	S	Si	V
Aermet	70.72	0.21	12.3	3.12	0.90	1.19	10.5	0.01	0.01	1.03	–
4340	95.77	0.40	–	0.80	0.70	0.25	1.83	0.035	0.04	0.22	–
300M	93.97	0.42	–	0.82	0.82	0.38	1.87	0.007	0.001	1.64	0.07

was reported to be less effective when both clad and substrate material were the same, as the rapid solidification rate leaves the clad area too brittle to improve the mechanical performance [9]. While post clad heat treatments improved the performance of the repaired sample, better results were achieved when Aermet®100 was substituted as the clad material due to its enhanced ductility. This result is of great interest to the application of laser-clad repair, as optimal performance might only be possible by varying the composition of the clad.

A downside to mixing various clad/substrate combinations is the risk of forming various defects related to particular metallurgical compositions [22]. This is due, in part, to a complex series of thermal cycles [26], rapid solidification and large thermal stresses owing to the very high heating/cooling rates (~10^4–10^6 K/s [27,28]). Macro-segregation effects can manifest when there is a difference in liquidus temperature between the two materials, as one material may solidify before it is fully mixed into the other [29,30]. This results in distinctive solidification patterns, which vary depending on the difference in melting temperature and whether the clad or substrate solidifies first. Even where the materials are perfectly mixed, certain material compositions experience an increased sensitivity to cracking during deposition [16,31], which would ruin any repair application.

Several different cracking mechanisms have been proposed to operate within separate temperature ranges during cladding [17]. Solidification cracking (often known as hot tearing) operates in the semi-solid state (i.e. between the liquidus and solidus temperatures) where dendrite growth prevents liquid feeding of shrinkage into intergranular regions [32,33]. The regions of entrapped liquid can then act as crack initiators should the cohesive strength between dendrites be insufficient to compensate the residual stresses from solidification and thermal gradients. Furthermore, depending on the alloy composition, brittle interdendritic phases can provide a fracture path under stress [17]. Another cracking mechanism is liquation cracking, where rapid heating to just below the solidus temperature causes preferential melting of low melting point non-equilibrium phases or eutectics [17,34]. In this case, internal stresses again initiate cracks at the weak solid/liquid interface. Another mechanism operates at lower temperatures and is referred to as ductility dip cracking (DDC) [17], strain-age cracking (SAC) [16], or simply “reheat cracking”. In this case, the material is re-heated to temperatures sufficient for precipitation of fine particles along grain boundaries. The resultant drop in ductility at these boundaries may then be sufficient for shrinkage stress to cause fracture. The above processes are not unique to laser cladding, but also occur in certain welded alloys [30,35]. Indeed, these issues are mostly understood for known alloy compositions, which are designated sensitive to hot cracking. However, in the case of dissimilar materials in laser cladding, dilution of the clad with the substrate produces a composition where the results are unknown, potentially jeopardising the intended repair process.

Given the promising results of the previous Aermet®100/4340 clad/substrate combination [9], this paper investigates the use of Aermet®100 in the laser clad repair of 300M ultra high strength steel. Aermet®100 has a lower carbon content than 300M, but also a significantly higher content of other alloying elements. These compositional differences may have adverse effects on clad quality, and as such, a parametric study is conducted to test the sensitivity of the Aermet®100/300M combination to defect formation. Aermet®100/4340 samples are also tested to investigate minor changes in substrate composition on these parameters. Finally, a third group of 4340/300M samples are tested to investigate situations where clad and substrate are compositionally similar. Together, these results help shape the criteria for combining different clad and substrate materials for successful repair.

2. Experimental

2.1. Material preparation

Round bars of 300M and 4340 steel were received in the annealed condition and machined to a diameter of 30 mm. AISI 4340 and Aermet®100 metal powder was supplied by Sandvik. Ltd. in the form of gas atomised spherical particles having a size range of 45–106 µm. The chemical compositions for the 300M, 4340, and Aermet®100 steels are shown in Table 1.

2.2. Laser cladding

Laser cladding was carried out on a TRUMPF TruLaser Cell 7020 system equipped with a 3.0 kW disk laser and a coaxial laser cladding head with a focal length of 200 mm. The coaxial powder delivery system had a focal distance of 8.0 mm, with Helium as the carrier gas at a flow rate of 10 L/min. Argon was used as the shielding gas with a flow rate of 16 L/min. A number of cladding trials were conducted to determine the effect of laser power, laser traverse speed and powder feed rate. These parameters were arranged in an orthogonal array of experiments, with the respective values shown in Table 2. An example of the as-clad bars is shown in Fig. 1. Both single and multiple clad tracks were conducted, with a spot size for all samples of 1.3 mm, and the step-over distance for multiple tracks was set at 0.65 mm. Multiple trials were conducted on the same bar, which was allowed to cool to room temperature between runs to ensure consistency of results.

2.3. Material characterisation

The clad bars were cross-sectioned using electrical discharge machining to prepare samples in the longitudinal (direction of laser travel) and transverse (across multiple tracks) directions. The samples were then mounted and polished to a 1.0 µm finish. These samples were then

Table 2
Process parameters and microstructural observations for specimens clad with Aermet®100. The base material is given below.

Sample	Laser power	Traverse speed	Powder feed rate	Observations	
	(W)	(mm/min)	(g/min)	4340	300M
1	600	1050	3.86	Lack of fusion	Large cracks
2	600	1400	5.15	″ ″	″ ″
3	600	1750	6.44	″ ″	″ ″
4	800	1400	6.44	″ ″	″ ″
5	800	1750	3.86	Fine cracks	″ ″
6	800	1050	5.15	″ ″	″ ″
7	1000	1750	5.15	″ ″	″ ″
8	1000	1050	6.44	″ ″	″ ″
9	1000	1400	3.86	″ ″	″ ″