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Microstructure and phase evolution in laser rapid forming of a functionally graded Ti–Rene88DT alloy

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Abstract

A graded Ti–Rene88DT superalloy material, which has potential uses in aero engines, was fabricated using laser rapid forming. A continuous compositional gradient from 100 wt.% Ti to 60 wt.% Rene88DT was achieved. The solidification behaviour and phase morphological evolution of the compositionally graded material were investigated. The study showed that a series of phase evolutions along the compositional gradient occurred: $\alpha \rightarrow \alpha + \beta \rightarrow \alpha + \beta + Ti_2Ni \rightarrow \beta + Ti_2Ni \rightarrow Ti_2Ni + TiNi \rightarrow TiNi$. The phase transformation and microstructural evolution along the compositional gradient were analysed by considering the thermodynamic conditions as well as using microstructure selection models based on the maximum interface temperature criterion. The results were summarized in a microstructural selection map for the Ti–Ni system. The hardness value of the graded material was measured along the compositional gradient and the results were explained in terms of the presence of the various phases.

Keywords: Laser rapid forming; Titanium alloy; Nickel alloy; Functionally graded materials; Phase transformations

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1. Introduction

In the last 50 years or so, material and manufacturing technology advances have expanded the range of applications of superalloys, which include turbine blades and vanes in aircraft jet engines and gas turbines in power generators. Superalloys are particularly well suited for applications requiring extremely high strengths at elevated temperatures with long exposure times. Indeed, more recently Ni-based superalloys are making inroads into the automobile industry for applications such as the components used in turbochargers and exhaust valves [1]. In some of these applications only certain regions of a component will encounter extremely high-temperature environments, and for such cases the components need not be fabricated out of mono-composition alloys, but rather the use of compositionally or functionally graded materials (FGMs) could be more appropriate. In so doing, the cost of the material and the final weight of the component could be reduced. For example, if Ni-based components can be fabricated using Fe-base/Ni-superalloy or Ti-base/Ni-superalloy FGMs, according to the requirements of working temperatures and properties, then significant savings in material cost and weight could be achieved.

Since the inception of Japan's FGMs programmes in the mid-1980s, FGMs have become one of the major current themes in structural materials research. FGMs have attracted much attention, since their composition and properties can be tailored to suit specific engineering applications, and their advantages over homogeneous materials are apparent [2]. Among the few processing methods for making FGMs [2,3], the laser rapid forming (LRF) of bulk near-net-shape metallic components using the solid freeform fabrication route has been shown to be a viable and promising manufacturing technology. Its main advantage

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over others is the freedom to clad selectively different elemental powders or premixed blends in discrete locations; this together with the use of multiple powder feeder systems and computer-aided design technology make the fabrication of FGMs without the application of a mould a reality. This technology is ideal for making prototypes in the automotive and aerospace industries, since they face long lead times of several weeks or even several months for producing functional, fully dense, and metallurgically good-quality prototypes. In this regard, direct LRF can certainly lower the cost and drastically reduce lead times by eliminating the pre- and post-processing steps and the need for specialized tooling. Since this technique has many advantages, many methods using a similar principle of fabrication have been developed [3–8]. It should be noted that most of the present research on LRF still concentrates on homogeneous materials.

Although quite a few studies have been conducted on the LRF of FGMs [3,9–18], only a few concerning superalloys can be found in open literature [3,12–15]. Kahlen et al. [12] employed the laser deposition of metal layers to create graded materials by varying the composition of the parts from 100% SS304 stainless steel to a 100% nickel-based superalloy. They only briefly studied the effects of the solidification rate on the mechanical properties of the graded materials. Brooks et al. [13] and Lewis and Schlienger [14] developed precise multiple-powder feeding capabilities for the LENS™ and DLF processes, respectively. These processes have been used to fabricate graded or layered material parts, and have been used for the preparation of SS316/In690, SS316/MM10, Ti/Ti20Nb, and Ti6Al4V/In718 graded materials. They also performed chemical and microstructural analyses of the FGMs that were produced by LRF. Recent work [3,15] by the authors showed that graded SS316L–Rene88DT materials can be successfully fabricated using LRF, and they investigated in some detail the effect of compositional changes on phase transformations and microstructural evolution.

Much interest has been shown in the LRF of Ti-based alloy/Ni-based FGMs [13], since these materials are becoming serious contenders for applications in aero engines. Collins and co-workers [16–18] studied the deposition of graded binary Ti–V and Ti–Mo alloys and ternary Ti–Al–V alloys by the LENS™ process, starting from a powder feedstock consisting of a blend of elemental Ti, Al, and V (or Mo) powders. They also investigated the influences of compositional changes on microstructural evolution in these alloys. Notwithstanding this research work, our understanding of the solidification behaviour of LRF multi-component FGMs is still far from satisfactory, especially with regard to the non-equilibrium phase transformation of Ti–Ni-based multi-component alloy systems. With this in mind, the present work focuses on the solidification behaviour and phase evolution of Ti–Rene88DT FGM formed by LRF.

2. Experimental

The compositional graded material was fabricated using a LRF system that consisted of a 5 kW continuous wave CO$_2$ laser from Rofin Sinar, a four-axis numerical control working table, and a powder feeder with a lateral nozzle. The experiment was conducted inside a glove box, the atmosphere of which was controlled. The laser was mounted on an overhead carriage and the beam was directed into the glove box through a window on top of the chamber. The controlled-atmosphere glove box was filled with argon gas, and argon gas was also used to deliver the metal powders to prevent the melt pool from oxidizing and oxide contamination from occurring during processing. The laser beam was directed onto the substrate to create a molten pool into which the premixed powders were injected. The metal powders were melted and subsequently re-solidified to form the clad layer. A solid structure with a rectangular profile was fabricated, with its first 5 layers ($\sim$2 mm) composed of 100 wt.% Ti. The composition of the deposition was then changed linearly from 100 wt.% Ti to 60 wt.% Rene88DT over the next 15 layers ($\sim$6 mm). Finally, an additional 5 layers ($\sim$2 mm) of 60 wt.% Rene88DT superalloy were deposited.

The delivery of the metal powders was conducted using a double powder feeder system with a pre-mix chamber. The first hopper contained pure Ti powders, while the second hopper contained Rene88DT powders. The powder streams from the two hoppers were first premixed in a flow chamber, and then the premixed powders were directly injected into the molten pool through the laser nozzle. The variation in composition along the height of the deposition was achieved by adjusting the ratio of the volume of Ti to Rene88DT superalloy through the regulation of the flow rates of the powders from the two hoppers according to the predetermined graded structure. The nominal compositions of Ti and Rene88DT superalloy powders are listed in Table 1. The processing parameters are presented in Table 2. The substrate material used for the experiment was a cold rolled Ti sheet. The surface of the substrate was cleaned by sandblasting prior to laser deposition. In order

Table 1
The chemical composition (wt.%) of the Ti and Rene88DT powders

	O	Cl	H	N	C	Si	Fe	Ti
Ti	0.18	0.02	0.004	0.018	0.02	<0.04	0.02	Bal.

	Cr	Co	W	Ti	Al	Nb	Mo	Ni	C