



Investigations on phase transformation and mechanical characteristics of laser additive manufactured TiNiCu shape memory alloy structures



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ABSTRACT

This paper reports laser additive manufacturing (LAM) of shape memory alloyed (SMA) structures using three premixed compositions of TiNiCu ($\text{Ti}_{50}\text{Ni}_{(50-x)}\text{Cu}_x$ ($x = 5, 15$ and 25)). A 2 kW fiber laser based additive manufacturing system was used. First, the processing parameters were optimized for defect free deposition, subsequently the optimized parameters were used for the LAM of the structures. These fabricated structures were characterized using scanning electron microscopy (SEM), atomic force microscopy (AFM), differential scanning calorimeter (DSC), X-ray diffraction (XRD), micro-hardness measurement and compression testing. SEM and AFM revealed the fine grain structures with good surface morphological characteristics ($<5 \mu\text{m}$ Ra value) for TiNiCu5. The ultimate compressive strength, modulus of elasticity and micro-hardness values for this sample was 451 ± 15 MPa, modulus of 28 ± 2 GPa and 237 ± 12 VHN, respectively. XRD confirmed the presence of two phases austenite and martensite in the LAM samples and DSC demonstrated low hysteresis between 22°C and 25°C , a prime requirement of SMA. The study paved a way for LAM of complex shapes using TiNiCu with all the prerequisite properties of SMA.

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1. Introduction

Shape Memory Alloys (SMA) are finding wide applications in various fields due to their unique properties in terms of super elasticity and thermal shape memory effect as reported by Laeng et al. (2007), Wu et al. (2008) and Li et al. (2009). Among various options, Ni-Ti alloys are primarily used as SMA as they have a large distortion in the lattice mechanizing the shape memory effect (SME). Since SME creates a broader hysteresis during the functioning, it sequentially reduces its life cycle. Fuentes et al. (2002) reviewed the research on SMA with the introduction of a third element (like – Pt, Hf, Zr, Fe, Nb, Al, Au, Cu) to standard binary Ni-Ti alloy. They reported that TiNiPt needed large number of training cycles to achieve the best results. TiNiHf was comparatively the cheapest among the options. But, even mild work hardening resulted in premature dislocation in the material effecting stress

induced martensite formation and led to gradual diminish of the shape memory effect in no time. TiNiZr has similar effect as that of TiNiHf with the difference only in the working temperature, (TiNiZr functioned at around high temperatures around 240°C). TiNiFe system was capable of working in very low temperature. TiNiNb generated high hysteresis where it could be deployed for short time applications. TiNiAl was also a good composition with efficient results but, it required a number of post processing (like – heat treatment) to achieve the SMA effect. TiNiCu did not bring much sensitivity in the transformation temperature neither high nor low. The hysteresis generated was far less among other options. Only Cu could successfully bond with Ni-Ti without disturbing its efficiency and characters in all aspects. The mechanical properties, like yield strength etc. of Ni-Ti with Cu were found to be at par with that of Ni-Ti. Another aspect of cycling stability and fatigue were also found to be good on the inclusion of Cu as mentioned by Fuentes et al. (2002). Chen and Wu (2001) successfully brought down the hardness by including Cu with Ni-Ti. Moreover, Du and Fu (2004) and Fu et al. (2011) confirmed the addition of Cu resulted in high nucleation rate and grain growth ensuring two-way shape memory effect in the fabricated material. In thick and thin films,

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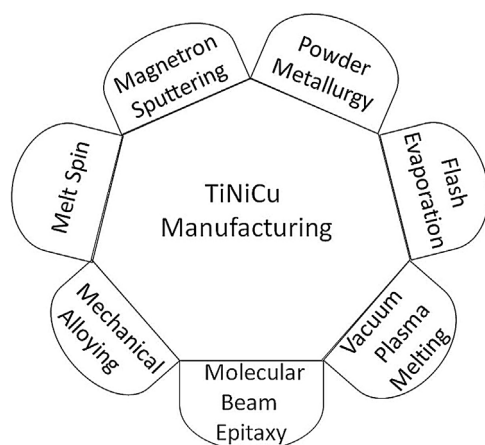


Fig. 1. Prevailing TiNiCu manufacturing techniques.

addition of Cu reduced the hysteresis and increased the recovery strain; it was a welcoming factor to opt for TiNiCu, as expressed by Nam et al. (1990) and Miyazaki and Ishida (1999). In published literature there are reports about the successful manufacturing of TiNiCu thin films using magnetron sputtering by direct deposition on various flexible substrates as well as glass substrates by Ren et al. (2000), Zhang and Qiu (2006) and Cai et al. (2007). TiNiCu ribbons by melt spin assisted with hot rolling was also successfully obtained by Goryczka et al. (2001). Gradually molecular beam epitaxy deployed by Hassdorf et al. (2006) and flash evaporation by Mineta et al. (2011) also caught attentions in the list of TiNiCu manufacturing methodologies. Veleanu et al. (2011) demonstrated promising results using powder metallurgy and vacuum plasma melting assisted with hot rolling was opted by de Araújo et al. (2011), while Alijani et al. (2014) demonstrated the manufacturing of TiNiCu using mechanical alloying. Fig. 1 summarizes the prevailing manufacturing technique of the fabrication of TiNiCu SMA. It may be seen in literature that these processes were successful in manufacturing thin films in simple geometries, but had limitations in scaling up to the complex structures due to inherent issues of process control.

It is well established that LAM has ability to manufacture complex products without changing the physical and chemical properties as in reported by Paul et al. (2007a,b, 2013a,b) and Ganesh et al. (2010). Also, the similar successful results were revealed in our previous attempts as reported in Shiva et al. (2015)

of fabricating SMA using LAM. From the literature survey, it is clear that the manufacturing of TiNiCu using LAM has not been reported in published literature. Hence, a systematic investigation on the feasibility of LAM of TiNiCu has been under taken. Three compositions of premixed powders were selected to fabricate the brick-like structure and thus-fabricated structures were examined for surface morphology, microstructural analysis, micro-hardness measurement, mechanical property evaluation and shape memory effect analysis. The properties of as-fabricated TiNiCu structures of these different compositions were also compared and the best combination was identified for the fabrication of SMA devices.

2. Experimental procedure

A 2 kW fibre laser based additive manufacturing system was deployed for LAM of TiNiCu. The schematic diagram of the LAM system is presented in Fig. 2. Similar to the work of Paul et al. (2012), the system has a 5-axis workstation in a glove box, a computerized numerical controller, a coaxial nozzle and a twin powder feeder. A titanium plate of dimension 100 mm × 100 mm × 10 mm was used as substrate. The substrates were sand-blasted just before the experiments to increase the laser absorption during the deposition of the first layer. The experiments were carried out in controlled atmosphere of argon maintained at high purity level (O_2 and $H_2O < 25$ ppm). Based on earlier published reports by Mercier and Melton (1979), and Grossmann et al. (2009), three compositions of TiNiCu (Ti-50%Ni-45%Cu-5%, Ti-50%Ni-35%Cu-15%, Ti-50%Ni-25%Cu-25%) were selected for the present investigation.

The predefined composition of the powders were uniformly mixed using inverse kinematics based powder blender. In subsequent section, the powder ratios of TiNiCu Ti-50%Ni-45%Cu-5%, Ti-50%Ni-35%Cu-15% and Ti-50%Ni-25%Cu-25% are designated as TiNiCu5, TiNiCu15, and TiNiCu25, respectively.

The track is the basic entity of the LAM and its shape, size and quality defines the quality of the fabricated structure. A number of tracks at various combination of processing parameters were laid and they were analysed carefully. First the surface topography of the tracks examined visually for continuity and uniformity of the tracks were studied. Only tracks with uniform and continuous shape were screened-in for further examination. Subsequently, the screened-in tracks were cut transversely to the direction of deposition for examination of the cross-section. The tracks with aspect ratio (track width/track height) more than five were exceptionally good with no defects. Hence, they were chosen for further

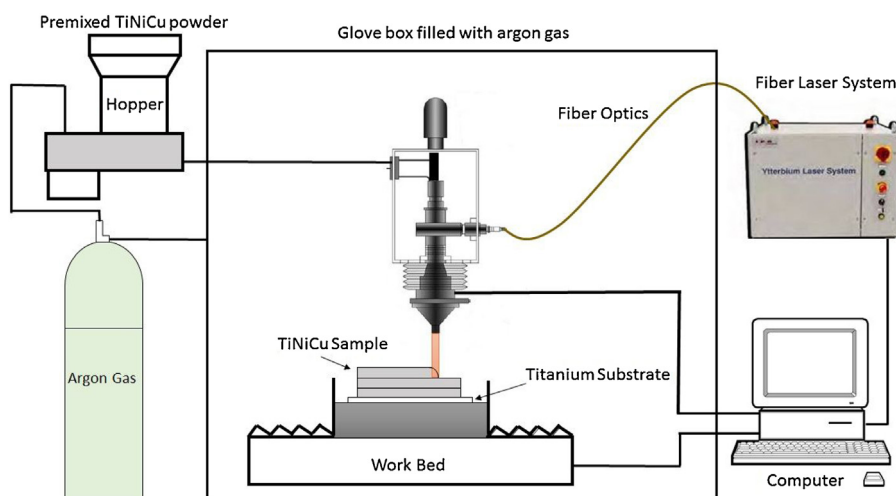


Fig. 2. Schematic diagram of 2 kW Fibre laser based Additive Manufacturing System fabricating TiNiCu samples.

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