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Mechanical and Thermal Expansion Behavior of Laser Deposited Metal Matrix Composites of Invar and TiC

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Abstract:

For laser assisted Shape Deposition Manufacturing (SDM), residual stresses caused by the temperature gradient and material property mismatches result in part inaccuracy, warpage, or even delamination. The use of low coefficient of thermal expansion (CTE) materials such as Invar promises to reduce deformations caused by internal stresses [2]. Thus, to obtain high quality of prototypes for molding and tooling, there is a need for a material with a low coefficient of thermal expansion, high yield strength, good toughness, and high wear resistance. This investigation concentrates on the development of laser-deposited composites of Invar and TiC. The experimental results show that the new materials yield exceptional low CTE, high hardness and yield strength, and reasonable ductility. The class of materials studied in this work promises to reduce deformation caused by residual stresses and improves mechanical properties significantly.

Keywords: Laser deposition; Metal matrix composites; Coefficient of Thermal Expansion; Mechanical properties

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1. Introduction

Shape Deposition Manufacturing (SDM) [1] is a layered manufacturing technique, which uses sequential steps of material deposition and removal to form three-dimensional structures. SDM has been used to fabricate parts out of metallic [1,2], plastic [3] as well as ceramic [4] materials.

For the fabrication of metallic parts, a laser has been added to the SDM process [2]. In Laser SDM, the part material is deposited with an intense laser beam which is focused onto the substrate where it creates a melt pool. Metallic powders from up to three different powder feeders are fed into the melt pool and subsequently melted. By moving the feed nozzle over the substrate according to the deposition path generated by the process planner, one layer can be deposited in near net shape. To obtain the final net shape, the layer is machined using a five-axis mill or an electric-discharge machine (EDM).

All layered fabrication processes based on melting deposition, such as Laser SDM, have in common that due to the large temperature gradients between the hot melt zone and the cold substrate the final parts suffer from residual stresses in the material [5]. These residual internal stresses are responsible for reduced part performance as well as warpage, loss of edge tolerance and even delamination of layered deposited parts.

To avoid these problems, the ideal part material for Laser SDM should have the following properties:

- A low coefficient of thermal expansion (CTE) over a wide temperature range, since internal stresses that occur during solidification and cool-down depend strongly on CTE.

- A high strength combined with good wear resistance and high corrosion resistance since one of the most intriguing applications of Laser SDM is Rapid Tooling.

It is the aim of the present work to develop such materials which can potentially reduce residual stresses in laser deposited parts significantly while maintaining or even improving all other properties (strength, toughness, corrosion and wear resistance).

2. Material Issues

Low CTE materials, such as Invar, will certainly be candidates to minimize the build-up of thermal stress. Invar is a 36%nickel-64%iron alloy with a very low coefficient of thermal expansion, near zero below temperatures of 300ºC. Above 300ºC the yield strength decreases rapidly (Fig. 1). This means that during solidification and cool-down of deposited Invar no elastic energy originating from thermal stresses can be stored in the material, because down to 300ºC the matrix is too soft to store a significant amount of elastic energy. Below this temperature the thermal expansion coefficient is low enough to avoid the buildup of further residual stresses. The use of Invar instead of stainless steel (SS 316L) reduces the deflection of test beams to one tenth of the original value [2]. However, Invar does not satisfy the requirement of Rapid Tooling due to its low yield strength, low wear resistance, and low corrosion resistance, especially at elevated temperatures. There is a need to improve its strength, wear resistance, and corrosion resistance while maintaining its exceptional CTE.

Laser processes have been used to enhance wear and corrosion resistance by surface alloying with hard particles. TiC as filler material increases hardness and wear resistance of the composite material [7-9]. TiC is most commonly used because of its extremely high hardness (33% higher than that of WC at room temperature), low specific gravity, and inertness. The resistance of TiC to oxidation even at elevated temperatures is well established. The CTE of TiC, 7.4 μm/(m K), is much lower than those of conventional metals.

The TiC phase ensures high hardness, wear resistance, corrosion resistance, and high strength while Invar provides exceptional CTE and toughness. Therefore, it is of interest to investigate the feasibility of metal matrix composites (Invar+TiC) fabricated by laser layered deposition.

3. Experimental Procedure

A 2400W, CW Nd:YAG laser is used to fuse the mixing powders of TiC and Invar. The laser power is controlled automatically and the deposition apparatus is moved across the surface of the substrate using a four degree-of-freedom robotic manipulator. By using this system, the composition of the deposit at any point on the surface can be accurately controlled. A 20 mm/s velocity, a 2000W laser power, and a 20 g/min deposition rate are controlled to form all experimental samples.

In this investigation, the powder size of Invar (Heat 502625) from Starmet Corporation is mesh -80 (-180 μm). The chemical composition of Invar powder is shown in Table 1. The particle size of TiC from Atlantic Equipment Engineers is from mesh -100 to +325 (45 ~150μm). The chemical composition of Invar powder is shown in Table 2.

3.1 Microstructural characterization

To check the microstructures of the composites, the specimens are deposited and machined to suitable sizes, then polished with SiC polishing paper to grade 1200, and with alumina powder to grade 0.05 μm. The etchant used for pure Invar consists of 5ml HNO_3 and 100 ml water while the etchant for the composites of TiC and Invar consists of 15ml water, 30ml HCl, 15ml HNO_3, and 15ml acetic acid. After etching, optical microscope, SEM, and XRD are used to characterize the microstructure of all the deposits with different contents of TiC.

3.2 Hardness test

The hardness can give some crude information on the mechanical strength of the material. 12.7 mm x 25.4mm x 25.4mm sized specimens are deposited uniformly in different contents, from 0 vol.% to about 50 vol.%, of TiC in an Invar matrix. The specimens are machined to obtain good surface roughness for Rockwell hardness tests. Scale C and scale B are both used due to the significantly varying hardness due to different contents of TiC particle in different specimens.

3.3 Tensile tests

To obtain accurate mechanical strength values of the composites, tensile tests are necessary. Specimens, deposited uniformly in different contents (from 0 vol.% to about 20 vol.%) of TiC inclusion, are machined for tensile tests. The gauge size of the samples is 6.35 mm x 6.35mm x 25.4mm.

3.4 CTE test

6.35 mm x 6.35mm x 25.4mm coupons are deposited uniformly in different contents, from 0 to about 20 vol.% TiC in an Invar matrix. The dilatometer method (ASTM E228) is used to measure the bulk CTE of the coupons.

3.5 Deflection test

One of the most important issues which limits the quality of parts produced with SDM is the accumulation of residual thermal stresses. These stresses, which result from fusing and constraining materials of differing temperatures [5], can cause warpage, delamination and surface finish defects in the final part. It is expected that the application of the new materials in laser SDM will reduce thermal stresses. To test the feasibility of the technique, a series of rectangular beams are produced to measure the relative deflections produced by depositions. In each of the tests, a single 2mm thick layer of material was deposited onto constrained steel substrates. The substrates are 150mm long, 25mm wide and 9.5mm thick low carbon steel. The maximum deflections of the bottom surface are measured. The composites of Invar and TiC and stainless steel 316L are used for this test. The deposition technique is a simple continuous scan of the laser across the surface.

4. Results

4.1 Development of microstructures

Typical microstructures of laser-deposited Invar with varying TiC content are shown in Fig. 2. In pure Invar (Fig. 2a) the grains are of spherical shape with about 5μm diameter. When 6.6 vol.% TiC is added, the character of the microstructure changes dramatically (Fig. 2b). The resolidified TiC and Invar leaves a dendritic structure.

When the TiC content increases to 22vol. %, the dendritic structure becomes even more obvious. At 29 vol.% TiC (Fig.2e) additionally to the dendrites some spherical particles can be seen. The non-dendritic grains become even more evident at 52 vol.% TiC (Fig. 2f). These spherical or cornered grains are due to un-molten TiC particles, which remain in their original powder-shape.

First X-ray diffraction experiments show only Fe-Ni and TiC structures in the composites. That suggests that only a little amount, if any, of TiC dissolves into the Invar structure. The composites may yield low CTE since matrix Invar might maintain its own microstructure, which is responsible for the exceptional CTEs.

4.2 Properties

As shown in Fig.3, the hardness of the reinforced Invar increased from 10 HRC (5 vol.% TiC) to 25 HRC (20 vol.% TiC) up to 55 HRC (50 vol.% TiC). Invar is relatively soft with a hardness of HRB 76. In Fig. 4 the yield strength of the composite material is plotted versus the TiC content. As expected, the strength increases significantly with increasing TiC reinforcement. The achieved strength of over 500MPa with 18 vol.% TiC is well within the range of useful materials for Rapid Tooling. The strength could even increase with more TiC content, but the machinability and toughness of the material would probably decrease accordingly. Figure 5 shows the ductility of the new composites. With higher TiC content, the elongation becomes shorter. Up to about 20 vol.% TiC, the elongation is about 5%, which is much lower than that of pure Invar (about 30%).

The most interesting question is, whether the coefficient of thermal expansion of the reinforced Invar remains low enough to give a significant decrease in thermal stresses compared to conventional Laser-SDM materials like stainless or tool steel. The average CTEs of pure Invar are about 1.88μm/(m·K) at the temperature range of 25~125 ºC and 3.6μm/(m·K) at 25~220 ºC, while that of pure TiC is 7.4 μm/(m·K). Average CTEs are measured through two temperature ranges: 25~125 ºC and 25~220 ºC. Average CTEs are plotted in Fig. 6. From Fig. 6 it can be seen that CTE of the composite stays well between the range given by the CTE of Invar and TiC. If there is some alloying between TiC and Invar, this does not seem to influence the low thermal expansion coefficient of the matrix material. The achieved CTE of all tested composites is well below the CTE of the materials used up to now (CTE of stainless steel is about 17 μm/(m·K)). The average CTEs with different TiC content are much lower than tool steel, mild steel, stainless steel, and aluminum alloy.

4.3 Beam deflection after deposition

Fig. 7 shows the measured deflections of the bottom surface of the steel substrate for different materials. The use of Invar reduces the deflections by a factor of 2 as compared to stainless steel. Using the composite with 0~20 vol.% TiC also reduces the deflections as compared to stainless steel, especially for those with TiC content less than 15 vol.%.

5. Conclusion

Laser deposition is capable of fabricating metal matrix composites of Invar and TiC. The experimental results show that the new materials yield exceptional low CTE, reasonable ductility, high hardness, and significantly improved yield strength. The class of materials studied in this work can reduce deformation caused by residual stresses and improves mechanical properties significantly compared to other materials used in layered manufacturing.

6. Acknowledgment

The authors want to thank Prof. Joanna Groza (University of California at Davis) for running the XRD experiments. The authors also acknowledge her input during valuable discussions.

7. References

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C	Mn	Si	P	S	Cr	Ni	Co	O	Fe
0.028	0.40	0.24	0.09	0.003	0.12	35.30	0.12	0.005	bal.

Table 1. Chemical Composition of Invar powder (weight %)

C	Free C	Fe	O	Ti
19.41	0.26	0.17	0.49	bal.

Table 2. Chemical Composition of TiC powder (weight %)

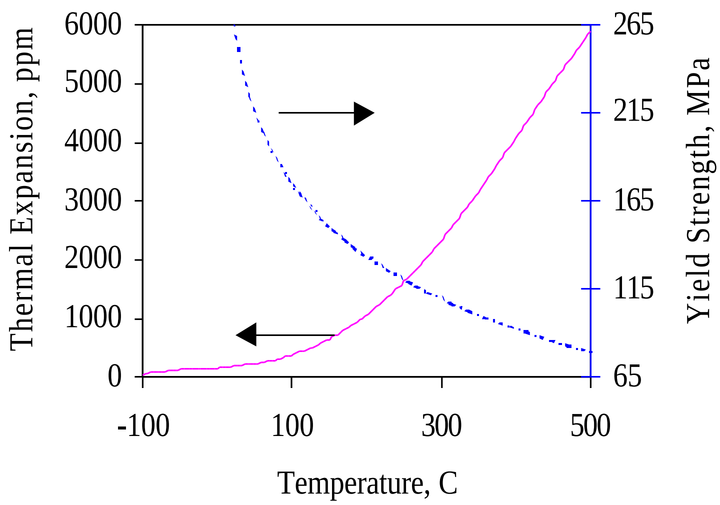
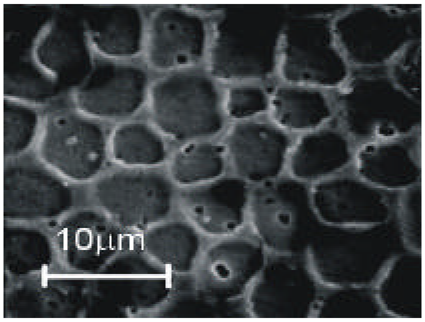
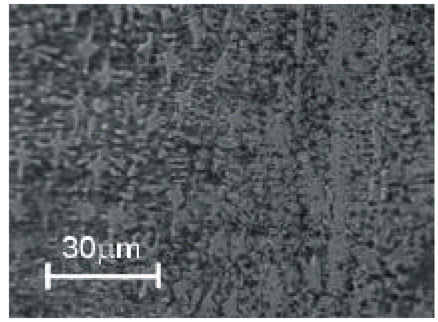


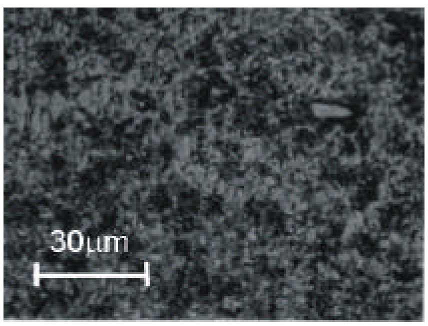
Fig. 1



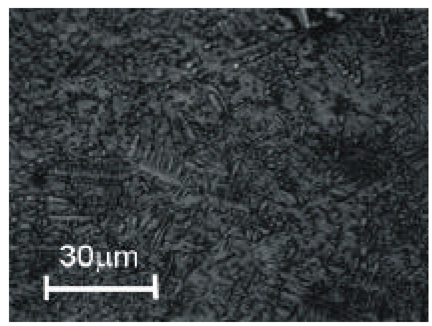
(a) 0% TiC



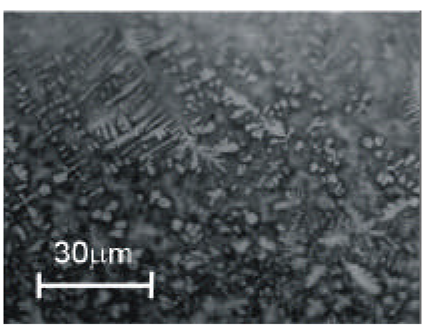
(b) 6.6 vol. % TiC



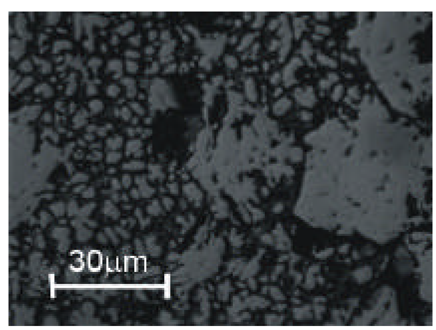
(c) 14.3 vol.% TiC



(d) 22.1 vol.%



(e) 29.4 vol.% TiC



(f) 52.1 vol.% TiC

Fig. 2

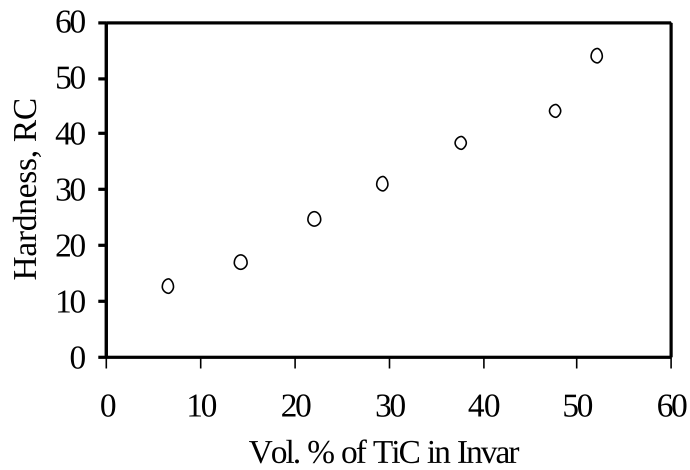

60
50
40
30
20
10
0
Hardness, RC
0
10
20
30
40
50
60
Vol. % of TiC in Invar

Fig. 3.

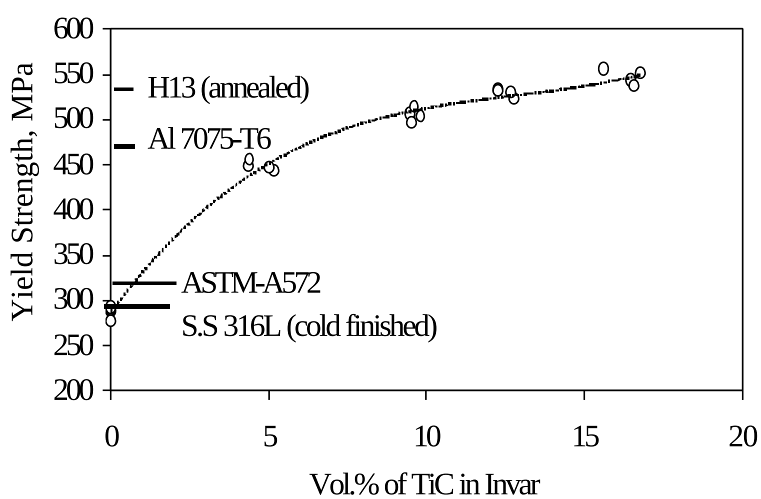

600
550
500
450
400
350
300
250
200
Yield Strength, MPa
H13 (annealed)
Al 7075-T6
ASTM-A572
S.S 316L (cold finished)
0
5
10
15
20
Vol.% of TiC in Invar

Fig. 4.

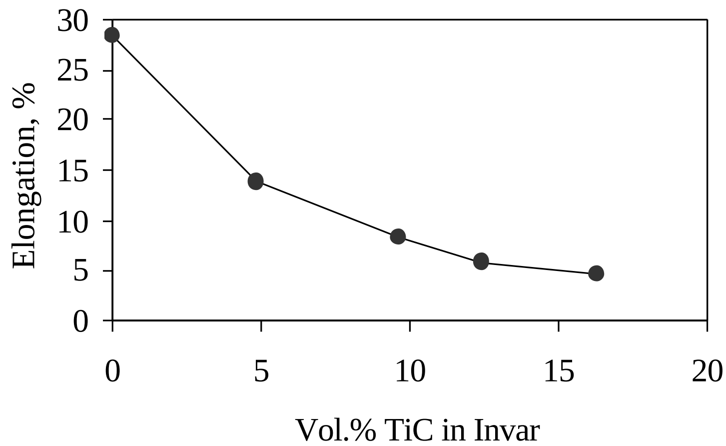

30
25
20
15
10
5
0
Elongation, %
0
5
10
15
20
Vol.% TiC in Invar

Fig.5

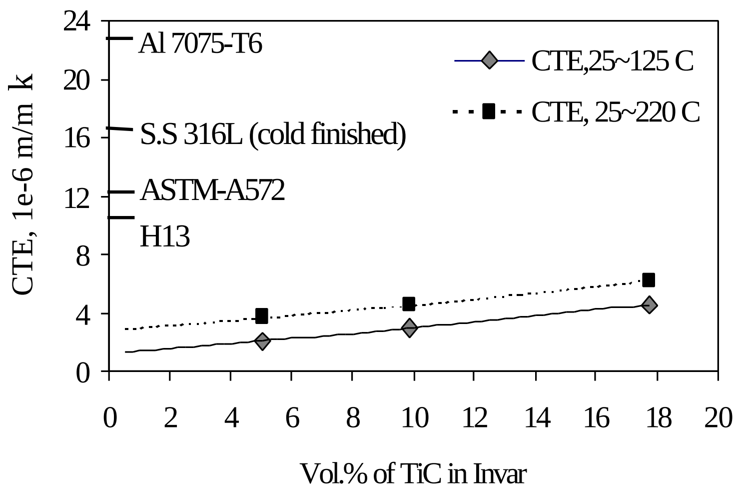

24
20
16
12
8
4
0
Al 7075-T6
S.S 316L (cold finished)
ASTM-A572
H13
CTE,25~125 C
CTE, 25~220 C
CTE, 1e-6 m/m k
0
2
4
6
8
10
12
14
16
18
20
Vol.% of TiC in Invar

Fig. 6.

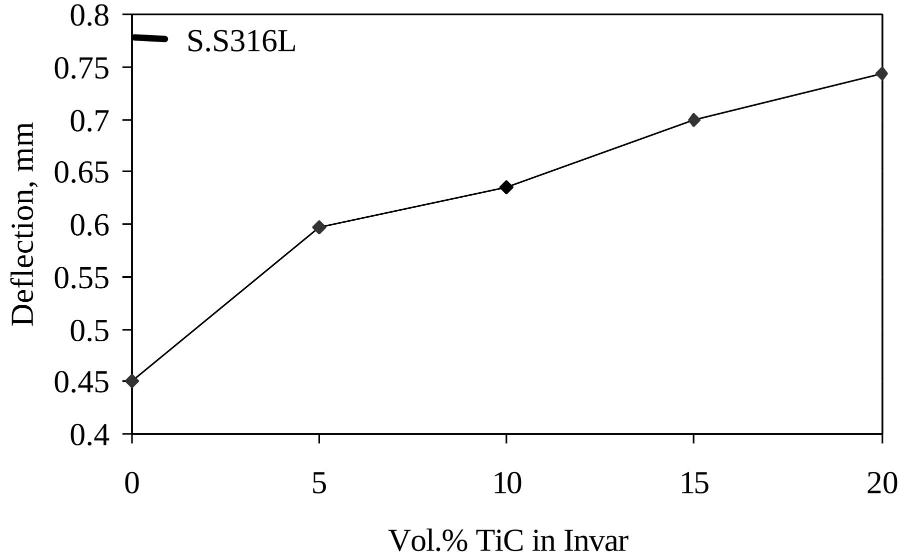

0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
S.S316L
Deflection, mm
0
5
10
15
20
Vol.% TiC in Invar

Fig. 7.