44th **Int. SAMPE Symposium**, L.J.Cohen et al. (eds), Long Beach, Vol 44(2) pp1849-1856, May 1999

DESIGN AND FABRICATION OF MATERIALS FOR LASER SHAPE DEPOSITION MANUFACTURING

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ABSTRACT

Shape Deposition Manufacturing (SDM) is a layered manufacturing technique, which uses sequential steps of material deposition and removal to form 3-D structures. A Nd-YAG laser is used to produce fully dense, near net shape multi-material deposits. However, residual stresses caused by the temperature gradient and material property mismatches result in part inaccuracy, warpage, or even delamination. To obtain high quality of prototypes for molding and tooling, there is a need for a material with low coefficient of thermal expansion (CTE), 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. By gradually changing the volume percentages of TiC in the deposits, parts with tough cores and hard surfaces can be built without distinct interfaces. The class of materials studied in this work promises to reduce deformation caused by residual stresses and improves mechanical properties significantly.

KEY WORDS: Laser Shape Deposition Manufacturing, Coefficient of Thermal Expansion, Metal Matrix Composites

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.

An off-line process planner is used to slice the CAD solid model into layers of varying thickness. The layer thickness is dictated by the geometry of the part and layer boundaries are strategically inserted at heights where there are transitions between undercut and non-undercut surfaces. This adaptive layer splitting reduces build-time by reducing the number of layers to the theoretical minimum, and five-axis shaping eliminates the stair-step effect found in other layered manufacturing techniques.

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 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 (see 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 [6]. 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.

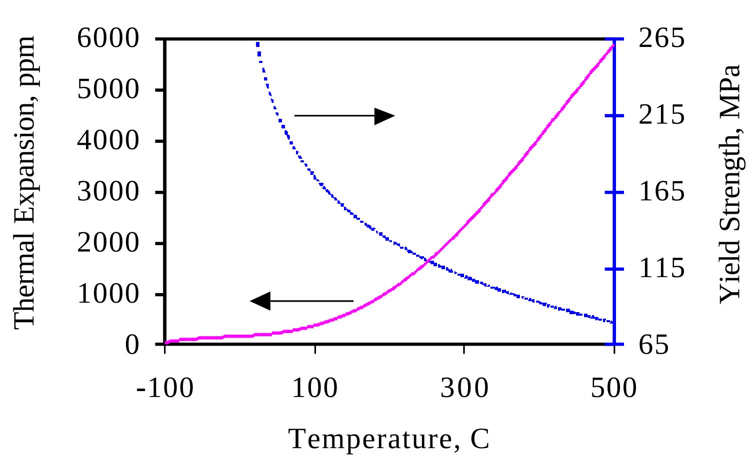


Figure 1. Thermal expansion and Yield Strength of Invar

For applications in Rapid Tooling Laser-SDM also offers the possibility to manufacture multi-material components. Using this technique the material properties can be tailored locally. For example, a tool for injection molding can have a hard and wear resistant outer surface with a rather soft core which gives the whole tool additional toughness. Traditionally, the common method to achieve that is through coating. Unfortunately, the coating material and the primary part material typically yield very different properties, such as CTE. Thus the interface is a source for possible failures. A new class of materials called Functionally Gradient Materials (FGM) [10,11] is a possible solution for the problem. By a spatial variation of the composition, microstructure and properties can be tailored locally.

3. EXPERIMENTAL PROCEDURE

A 2400W, CW Nd:YAG laser is used to fuse the mixing powders of TiC and Invar. The powders are pre-placed on the surface of a low carbon steel substrate from a single powder feed nozzle. 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). Chemical elements in the Invar powder are listed in Table 1:

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 Elements in Invar Powder (weight %)

The particle size of TiC from Atlantic Equipment Engineers is from mesh -100 to +325 (45 ~150μm). Chemical elements in the TiC powder are listed in Table 2:

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

Table 2. Chemical Elements in TiC Powder (weight %)

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 15 ml water, 30 ml HCl, 15 ml HNO_3, and 15 ml 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 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 Test 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.

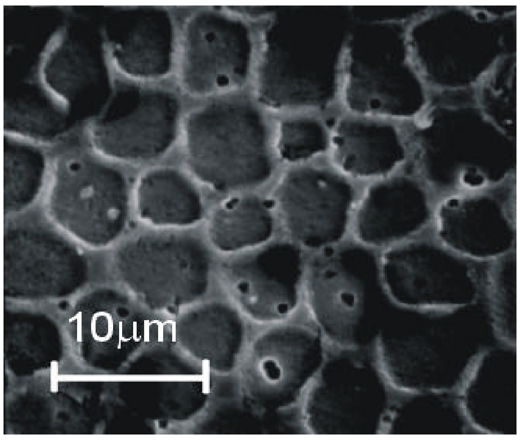
3.5 Functionally Gradient Combination of TiC and Invar Specimens are deposited gradually varying compositions from 0 to 30 vol.% TiC in the Invar matrix over a span of 50mm.

4. RESULTS

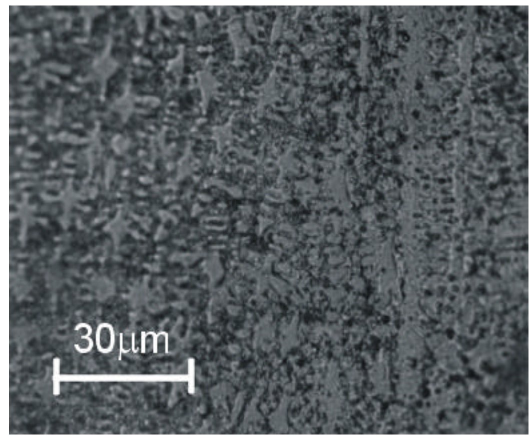
4.1 Development of Microstructures Typical microstructures of laser-deposited Invar with varying TiC content are shown in Fig. 2. In pure Invar (Fig. 2a) the grains are of spherical shape with about 5μm diameter. When 6.6 vol.% TiC is added, the character of the microstructure changes dramatically (Fig.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

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

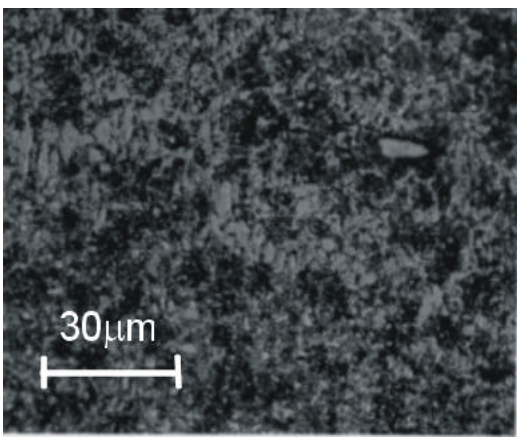
First X-ray diffraction experiments show only FeNi and TiC structures in the composites. That suggests that little amount, if any, of TiC dissolves into the Invar structure. The composites may yield low CTE since matrix Invar might maintain its own microstructure, which is responsible for the exceptional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



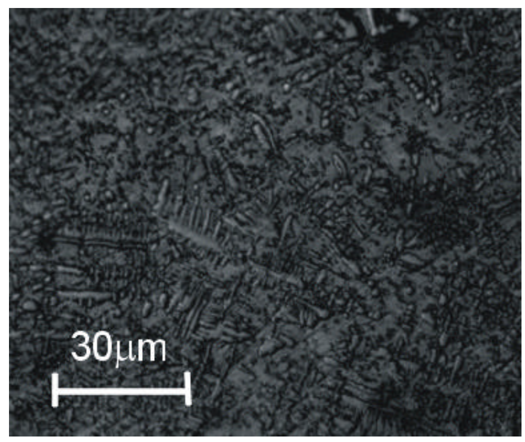
(a) 0% TiC



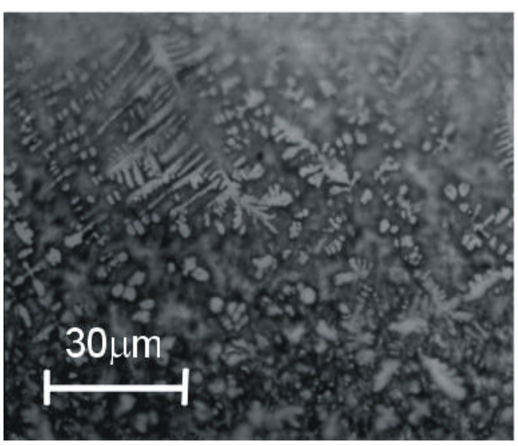
(b) 6.6 vol. % TiC



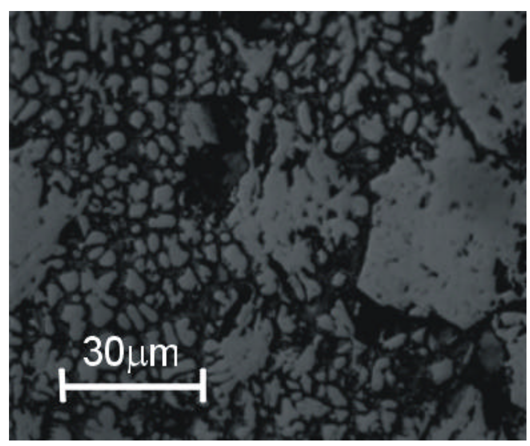
(c) 14.3 vol.% TiC



(d) 22.1 vol.% TiC



(e) 29.4 vol.% TiC



(f) 52.1 vol.% TiC

Figure 2. Typical Microstructures of Invar with Different TiC Content

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.

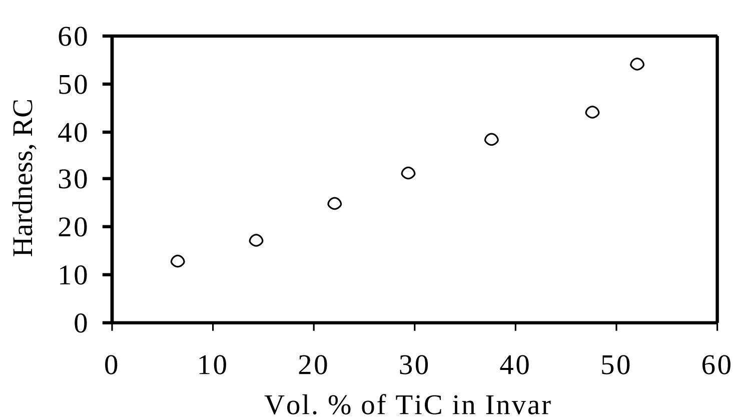


Figure 3. Hardness Test Results

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.

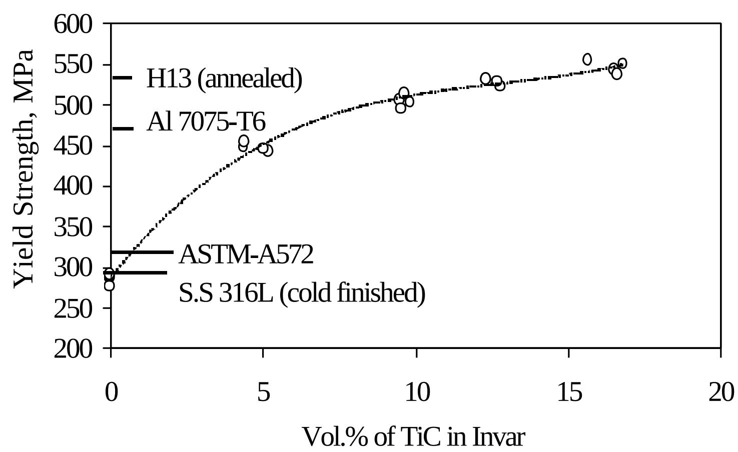


Figure 4. Yield Strength of Composites

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 Figure 5. From Fig. 5 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.

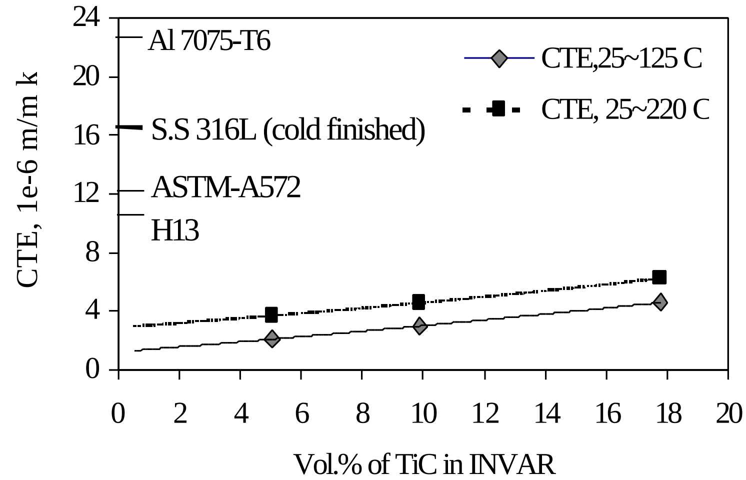


Figure 5. CTE of Composites in Comparison with Metals

4.3 Functionally Gradient Deposition Fig. 6 show that the distribution of hardness (Rockwell B scale) versus location for samples of the graded material which transitions from 0 vol.% to 30 vol.% TiC over a span of 50 mm. While there is essentially a linear distribution of the TiC content, the hardness distribution is non-linear. However, hardness is still a continuous, smooth variation so any desired hardness can be obtained through accurate mixing of these two powders. The results approximately match the hardness results (see Fig. 3) which are shown in Rockwell C scale.

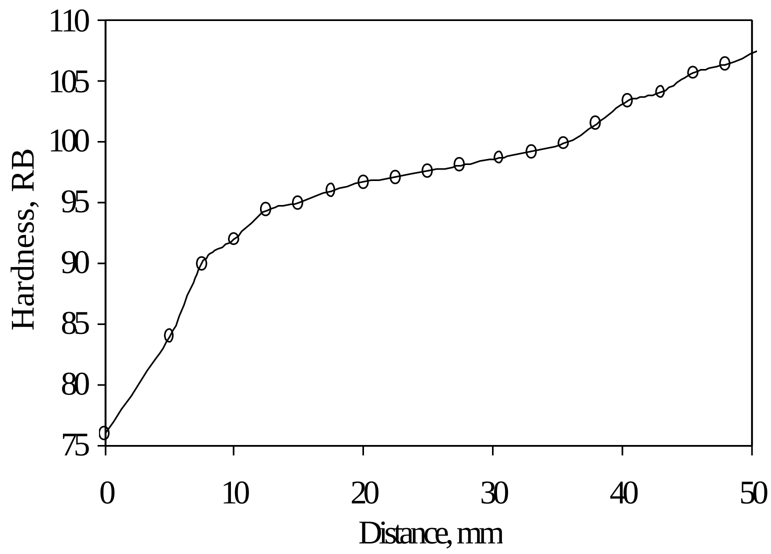


Figure 6. Hardness of Functionally Gradient Deposited Invar and TiC

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, high hardness, and significantly improved yield strength. By gradually changing the content of TiC in the deposits, Functionally Gradient Materials of TiC and Invar have been developed for Laser SDM to build functional parts. The class of materials studied in this work promises to reduce deformation caused by residual stresses and improves mechanical properties significantly compared to other materials used in layered manufacturing.

6. ACKNOWLEGEMENT

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.

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