Functional Gradient Metallic Prototypes through Shape Deposition Manufacturing

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Abstract

Stanford's SDM laser deposition system has been recently improved to enable the deposition of functionally graded metals through the use of powder mixing. While Shape Deposition Manufacturing has always had the capability to produce multimaterial artifacts, powder mixing enables the deposition of single layers in which material properties can be smoothly varied without discrete interfaces between dissimilar materials. It has been shown that certain materials will completely mix during deposition and form alloys which exhibit material properties intermediate to those of the constituent feed powders. To date, oxidation and hardness have been effectively controlled through appropriate mixing of powders. Functional gradient material deposition has been exploited to construct an advanced injection molding tool which transitions from Invar in the center to stainless steel on the outside. The resulting tool exhibited minimal distortion from thermal stress and excellent exterior corrosion resistance.

Introduction

A functional gradient material is a single, solid piece of material which exhibits spatially varying material properties. By creating such materials, one can tailor the composition of an artifact such that material properties are locally optimized. For example, for optimal tool life it is desirable to have a hard outside shell for wear resistance and a ductile core to resist brittle fracture. Traditionally, such benefits have been achieved through the coating or cladding of existing artifacts with shells of different physical characteristics. While these techniques have been used extensively with great success, problems can result from sharp interfaces between dissimilar materials. Internal stresses and coefficient of thermal expansion mismatches can result in delamination, and the sharp interface can act as an initiation site for fracture. A monolithic structure with smoothly varying composition could alleviate some of these problems. Objects with extremely complex geometry can also be difficult to coat or clad effectively. If these complex parts were built in a layered fashion, any surface could be effectively coated regardless of the geometric complexity.

Shape Deposition Manufacturing (SDM) [1, 2] presents the possibility to create metallic artifacts with functional gradient materials. SDM uses laser deposition to fuse metallic powders onto a substrate and these powders can be mixed to create a range of alloys. For example, one can a produce a solid sample of stainless steel with a smooth variation in hardness from 20 and 45 Rockwell C (R_C) simply by mixing hard and soft powders in the proper ratio. By depositing these materials in layers, SDM enables the production of objects in which functional gradient materials are used throughout the volume of the object. For example, artifacts with alternating layers of soft and hard materials are expected to be much less susceptible to failure through fatigue. As shown in bimaterial structures [3], much of the crack energy is dissipated in the soft layer, preventing the penetration of cracks into the harder layer. By using SDM, one could realize the benefits of these layered materials in objects of arbitrarily complex geometry. This paper will examine some of the benefits and properties of the functional gradient materials produced with SDM. In particular it will examine the homogeneity of the deposits and the resulting material properties. Finally, it will present an example artifact which benefits from the use of functional gradient materials.

Laser Deposition System

The laser deposition system for producing functional gradient materials is essentially the same system described in Reference [2]. A 2400 W, continuous wave Neodymium:YAG laser is used to fuse metallic powders onto a substrate. The laser is focused onto the substrate where the transferred energy creates a melt pool. Metallic powders from three different powder feeders are fed from a single powder feed nozzle into the melt pool and subsequently melted. Mixing of the powders occurs in an input funnel and along the length of a 1.5m feed tube. The feed rate of each of the powders and laser power are controlled automatically and the deposition apparatus is moved across the surface of the part using a four degree-of-freedom robotic manipulator. By using this system, the composition of the metal deposit at any point on the surface can be accurately controlled.

Alloying of Metal Powders

The first issue regarding the mixing of metallic powders for laser deposition is whether a homogeneous material is formed during solidification. Because of inadequate mixing or melting, the resulting material could possibly be comprised of isolated islands of one material in a matrix of the second material. Such behavior would result in material properties significantly different than expected for a full alloy.

To investigate the degree of alloying, electron backscatter microscopy was performed on samples of 50% Invar and 50% 316L stainless steel. Such a material combination is of interest for SDM because Invar exhibits a very small coefficient of thermal expansion and stainless steel has high corrosion resistance. A combination of the two results in a part which has minimal distortion due to thermal stresses and can withstand the acid etch required to remove the copper support structure. Figures 1 and 2 show the composition of chrome and nickel for samples A and B versus location. In sample A, a sharp interface between the two materials was achieved by depositing stainless steel next to an already existing deposit of Invar. The transition from one material to the other occurs over the length of 1.5mm, which is approximately the overlap of one laser pass on another. Sample B was deposited in a continuous fashion where the composition was varied between 100% Invar and 100% stainless steel in 10 discrete increments over 50mm. Electron backscatter images at the midpoint of each sample are shown in Figures 3 and 4 for samples A and B respectively. In electron backscatter images, elements with high average atomic number appear lighter than those with low average atomic number. Figure 3 shows a distinctly lighter region of high atomic number material (Invar) separated from the darker, lower atomic number region (stainless steel) by a jagged interface. Figure 4 shows an image from sample B where the composition is 50% Invar and 50% stainless steel. This image has essentially uniform intensity, indicating a homogeneous composition. If the powders were not fully melting and mixing, one would expect to see pockets of light and dark on the order of the particle diameter (100 μm). Separate X-ray diffraction analysis shows that only a single phase is present in the material. This indicates that the constituents have formed a single-phase, solid-solution and are fully alloyed.

The alloying properties of Invar and stainless steel should be contrasted with those of Aluminum-bronze and 316L stainless steel. Deposits which transition from 100% bronze to 100% stainless steel show visible segregation of the two materials into distinct bands and significant cracking. Figure 5 shows an electron backscatter image of such a composition where there are dark regions of stainless steel surrounded by the lighter bronze. X-ray diffraction analysis of this sample shows multiple phases present in the material. Such segregation is not surprising considering that copper and iron have very low solubility below 1400°C at any concentration [4].

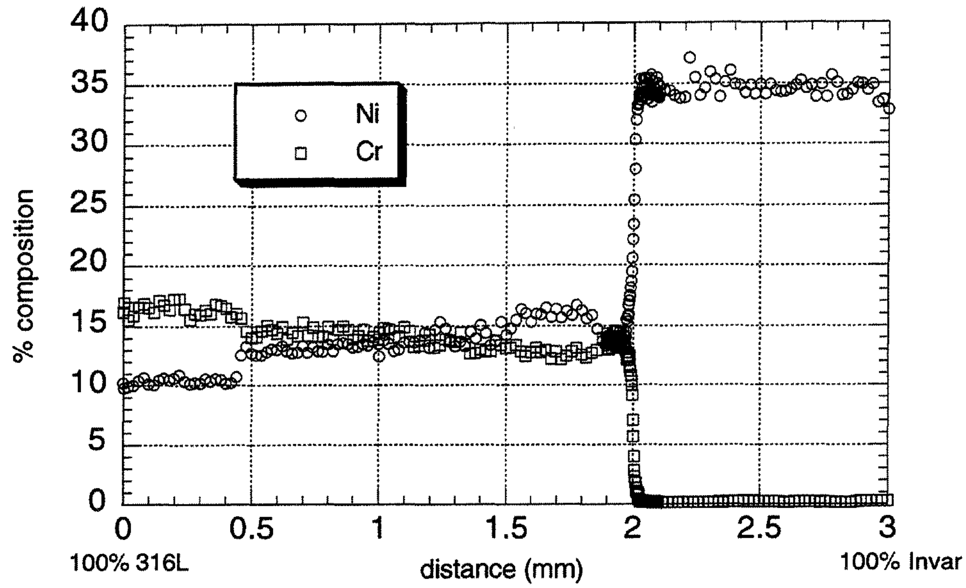

Figure 1: Composition of Chrome and Nickel versus location for a sharp interface between Invar and 316L stainless steel. (Sample A)

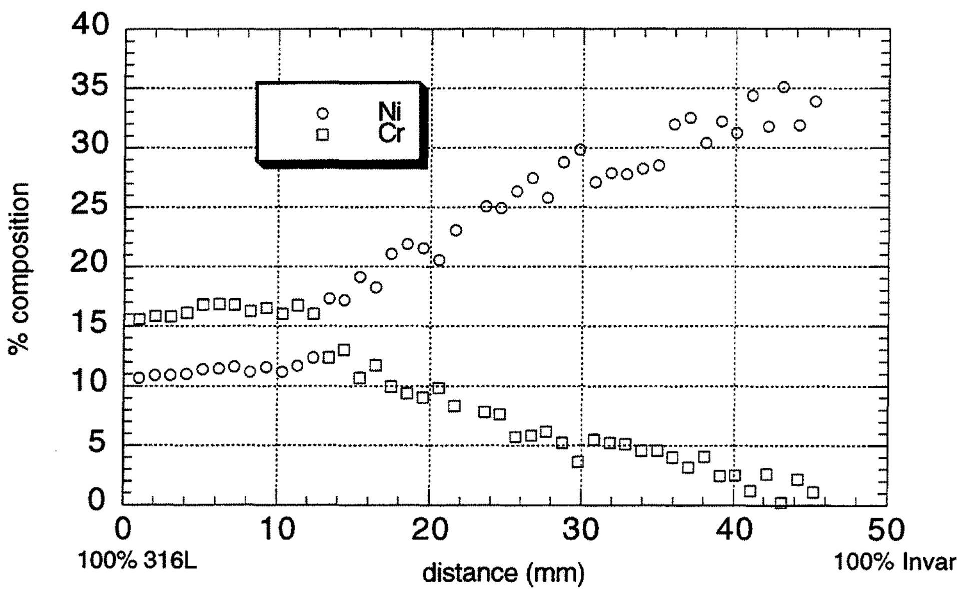

Figure 2: Composition of Chrome and Nickel versus location for a graded interface between Invar and 316L stainless steel. (Sample B)

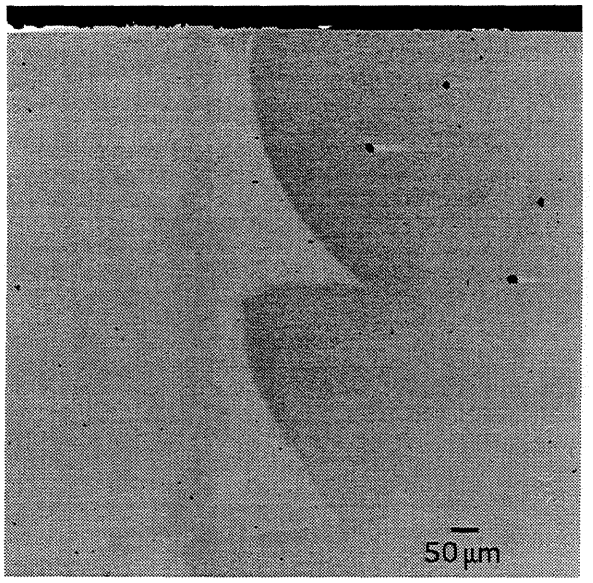

Figure 3: Electron backscatter image for Sample A at location of 2mm. Lighter shades indicate higher atomic number of Invar.

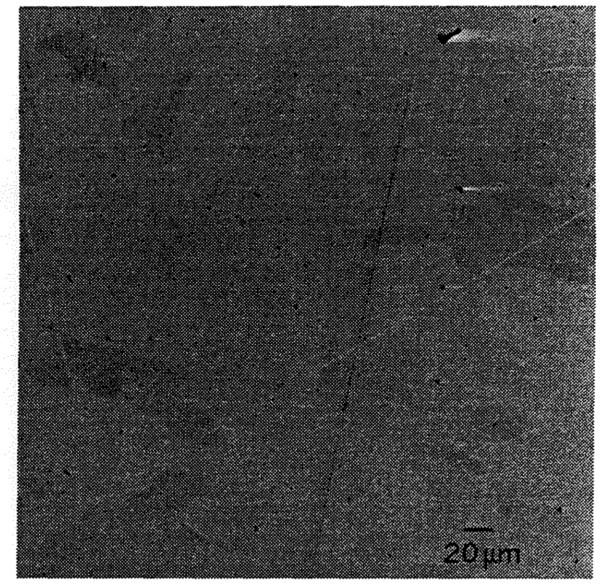

Figure 4: Electron backscatter image of Sample B at midpoint. Uniform shade indicates complete alloying of 50% Invar and 50% stainless steel.

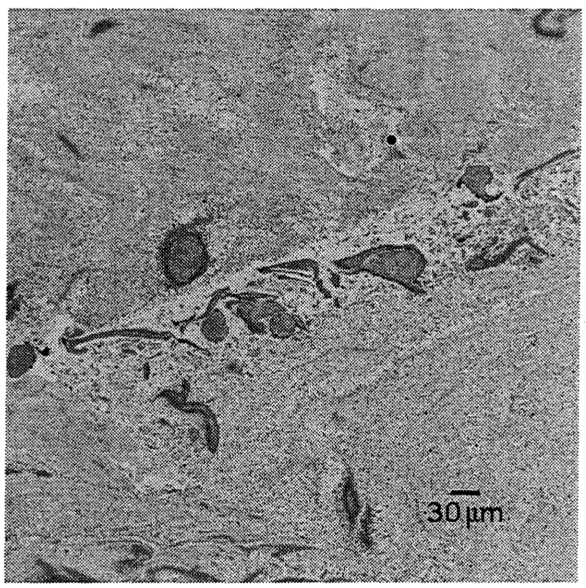

Figure 5: Electron backscatter image of aluminum-bronze and 316L stainless steel mixture. Note the distinct islands of stainless steel (dark) within the largely bronze matrix.

Properties of Graded Materials

Given that certain materials will fully alloy during the deposition process, one would expect the material properties in the graded sections to transition smoothly between the two extremes. This is indeed what occurs. For instance, in the Invar to stainless steel graded material illustrated in Figure 2, there is a continuous distribution of oxidation resistance which scales with the level of chrome. Invar, which has no chromium will oxidize to dark blue at elevated temperatures while stainless steel will remain silver. Figure 6 shows images of both the graded sample (Sample B) and the sharp transition samples (Sample A) after oxidation in a 400°C furnace for 25 minutes. Note the continuous distribution of oxidation in the graded sample.

Figure 6: Oxidation of sharp (Sample A) and graded transitions (Sample B) from Invar to stainless steel.

Invar-stainless steel transitions are especially important for the SDM process because the presence of Invar has been found to drastically reduce the amount of deformation resulting from residual thermal stresses. Pure Invar deposits show approximately 1/2 the deflection of pure stainless steel deposits of the same geometry [2]. Laser-deposited Invar, however, cannot withstand the long-term immersion in nitric acid that is required to remove the copper support material used in the fabrication of metal parts. A thin layer of stainless steel is sufficient to protect the part in the acid bath, and beams made with a core of Invar and a thin shell of stainless steel have been found to have only 2/3 the deflection of pure stainless steel beams.

As stated in the introduction, one of the most useful functional gradient materials involves a hard outer shell for wear resistance surrounding a more ductile core. The laser deposition system has been used to produce samples which continuously transition from 316L stainless steel ($R_c < 20$) to a harder, corrosion resistant alloy ($R_c = 43$) similar to 414 stainless steel. Figures 7 and 8 show the distribution of hardness and iron content versus location for a sample of this graded material which transitions from 100% hard alloy to 100% 316L stainless steel over 50mm. Note that while there is essentially a linear distribution of the iron content, the hardness distribution is distinctly non-linear. Most of the hardness variation occurs between 20 and 30mm which corresponds to concentrations of 40 to 60%. The plateaus on either side of this transition region correspond closely to the hardness of the major constituent. It should be noted, however, that hardness on the Rockwell C scale does not scale linearly with carbon in stainless steels and the nonlinearity can be qualitatively explained by the variation of carbon content. While the hardness variation is not linear, it is a continuous, smooth variation so any desired hardness between 20 and 45 R_c can be obtained through the proper mixing of these two powders.

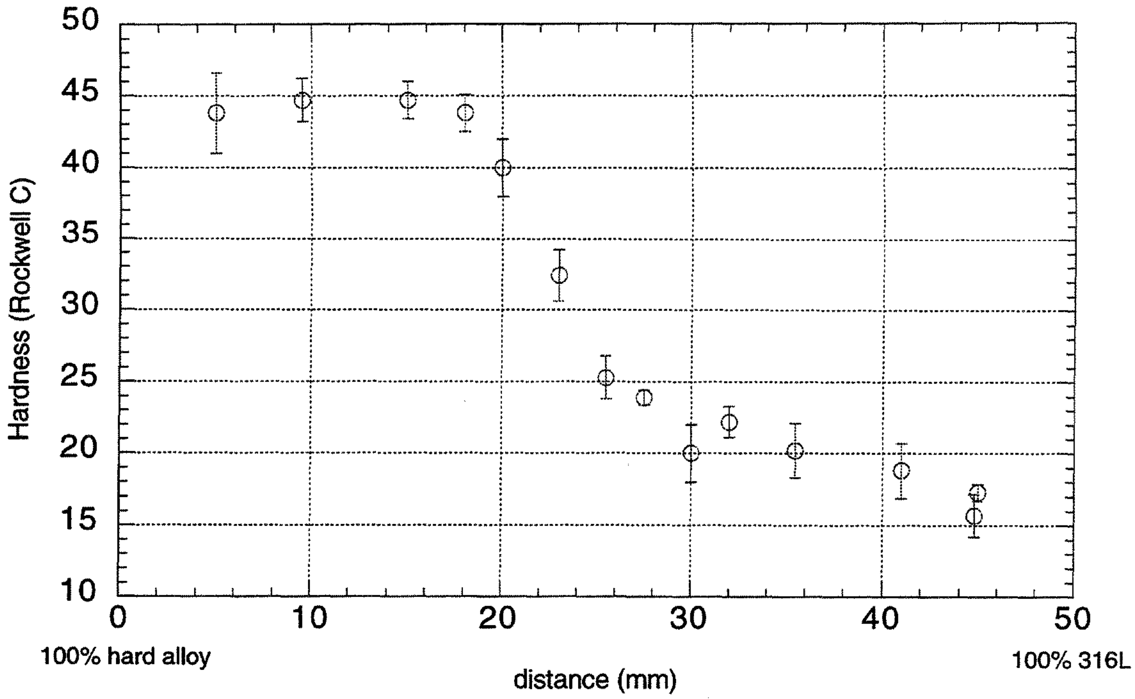

Figure 7: Hardness distribution for a hard alloy to 316L stainless steel graded material.

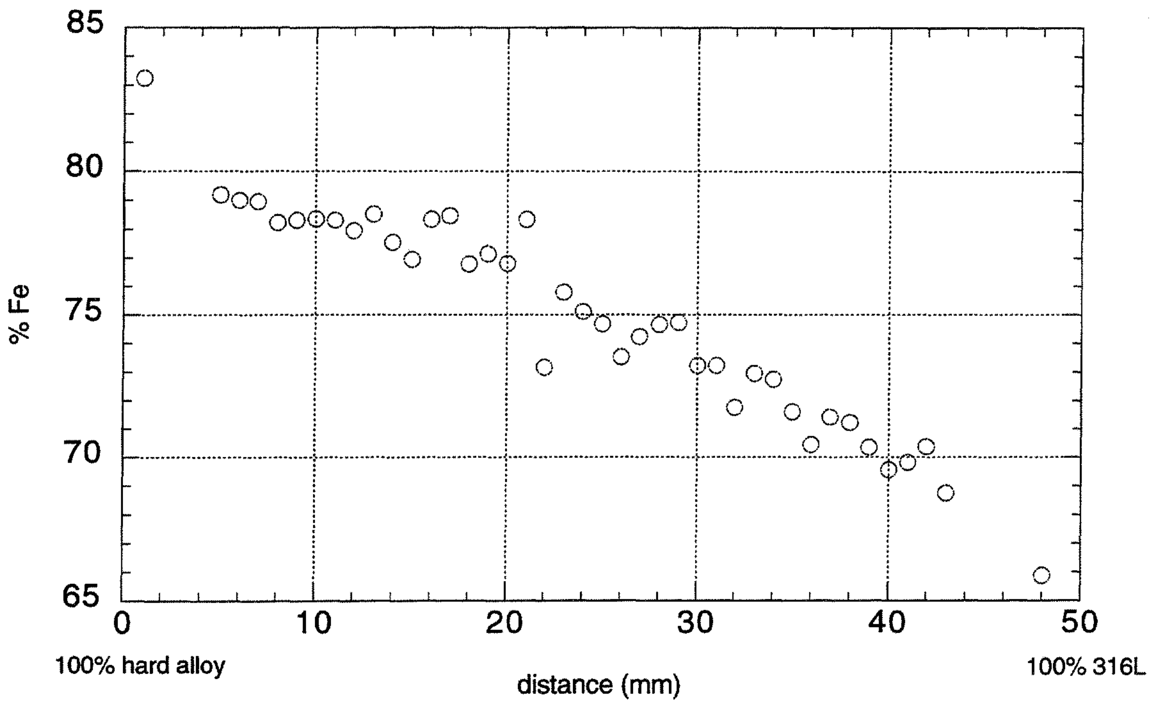

Figure 8: Iron concentration distribution for a hard alloy to 316L stainless steel graded material.

Functional Gradient Metallic Prototypes

The first application of functional gradient materials to SDM artifacts is an advanced injection molding tool designed by ALCOA. This tool, which is shown schematically in Figure 9, is comprised of three materials: Invar, stainless steel and copper. The bulk of the tool is made from Invar to reduce deformation due to residual thermal stresses. A thin shell of stainless steel surrounds the part to protect it during the acid etch process. To minimize cycle time, cooling channels would ideally be placed directly under the mold section of the tool; this, however, would not allow for ejector pins for part removal. As a compromise, solid deposits of copper have been located 2mm below the mold surface to facilitate heat removal form the part during production. Conformal cooling channels are located 2mm on either side of the copper to facilitate heat removal from the copper. The proximity of the copper to both the cooling channels and the plastic part should significantly decrease the cycle time for each part by reducing the time necessary for temperature stabilization.

Near net shape deposition of each layer began with Invar at the center of the part and spiraling outward following the geometry of that layer. In the outer few passes, a continuous transition was made from Invar to stainless steel to assure all outside surfaces were corrosion resistant. Internal features such as the cooling channels and the pocket for the copper deposit, were machined layer-by-layer as the part was deposited, while outside features were machined and electro discharge machined (EDM) after the entire part was deposited. Figure 10 shows a cross section of the part which shows the relative locations of Invar, stainless steel and copper. Construction of this part illustrated that continuous transitions between materials could be made within a single deposited layer. Future work will include tools with very hard outside shells to decrease tool wear and Invar cores to reduce thermal distortion.

Conclusions

The ability to specify material properties at any location within an artifact presents numerous benefits to designers in terms of choosing the optimal material for each application. Recently, the laser deposition system within SDM has been modified to enable the continuous deposition of graded metals from up to three constituent feed powders. This, coupled with the inherent flexibility of SDM, now enables the production of complex three dimensional artifacts with continuously varying material properties throughout the volume of the artifact. Materials which traditionally alloy also alloy with this system to form homogeneous, single phase deposited material. In general these graded materials exhibit varying material properties with varying composition but the property variations are not necessarily linear with concentration. The new system has been used to produce samples with continuously variable oxidation resistance and hardness. Future work on the material properties of these graded materials will focus on their fracture and fatigue properties as compared to sharp material interfaces.

The system has also been utilized to fabricate an advanced, multimaterial injection molding tool. The tool has copper deposits and cooling channels to minimize cycle time and Invar core to reduce distortion due to residual thermal stresses. The outside of the tool is stainless steel to prevent corrosion while in the acid bath used to remove the copper used as a sacrificial support material. The Invar and stainless steel were deposited in a continuous, outward spiral, where the transition to stainless steel was made within the outer few passes along the contour. The same technique could be also used to produce long-life, wear-resistant tools with a hard, corrosion-resistant outer shell. This technique can be extended to any multimaterial application where stress concentrations due to sharp material interfaces may limit performance.

Figure 9: Model of advanced ALCOA injection molding tool. Tool is made of Invar, stainless steel and copper and has two conformal cooling channels in each half to remove heat quickly from the part.

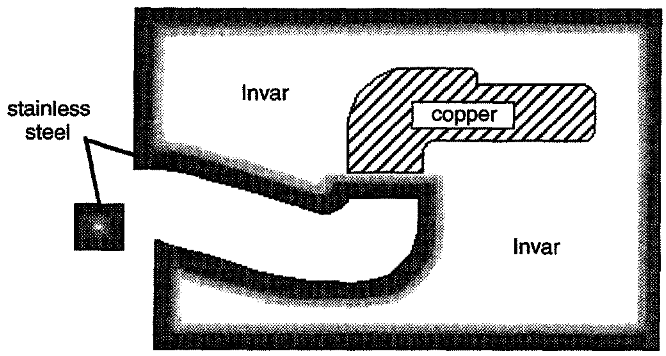

Figure 10: Horizontal cross-section of one half of advanced injection molding tool illustrating gradient from Invar to stainless steel on surface of part.

Acknowledgments

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