Reducing Part Deformation by Inducing Phase Transformation

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Abstract

Fabrication of solid freeform fully dense metal parts involves large temperature gradients and fast cooling rates. These conditions may lead to the accumulation of residual stress or part failure by deformation. However, in tool steels, certain phase transformations can cause volumetric changes, which have the potential to reduce part deformation and stress. This research optimized process parameters for inducing controlled phase transformation in Shape Deposition Manufacturing (SDM). By manipulating SDM laser deposition process parameters, the deformation of planar beams was significantly reduced or eliminated.

1. Introduction

Influencing or altering the microstructure of a formed object to achieve certain materials properties is a common aspect of producing viable parts. Heat treatment is often used to homogenize the microstructure of newly formed sand castings or machined metal prototypes to attain uniform hardness and reduce residual stress. The surface microstructure of metal parts like gears may be deformed by peening to impose compressive stress to increase wear resistance. Die surfaces may be impregnated with alloying agents to improve die life. Laser hardening has been used on camshafts to improve wear resistance.

Layered manufacturing techniques of solid freeform fabrication have the ability to influence or control the microstructure of the prototype. Like heat treatment and casting processes, laser deposition can affect the microstructure of the part. However, unlike these bulk processes, laser deposition techniques like surface cladding can have a more localized effect (Figure 1). Yang et al. [4] showed that a CO_2 laser hardening process can produce a microstructually altered region near a part's surface 350 μm thick.

Laser deposition produces rapid solidification or quenching because of fast heat conduction from the laser melt pool into the base metal. This solidification rate can also be influenced by changing deposition parameters such as scanning speed and laser power. When depositing carbon steels, rapid solidification can cause metastable phases to occur, primarily martensite. Martensite formation is a diffusionless process which occurs when the deposit cools from high temperatures (like the steel melting point) to below the martensitic start temperature in less than 10 sec. The arrows shown in Figure 2 illustrate the isothermal transformation of H13 and 410 stainless steel to martensite by rapidly cooling to room temperature. Cooling slower than this would not produce martensite but result in the production of ferrite and cementite.

When the laser melts the powder, the first solid metal to nucleate within the liquid is austenite. Austenite has a face center cubic structure. The rapid quenching causes the carbon in the austenite phase to transform to body center-tetragonal (BCT) martensite trapping carbon in the BCT lattice which has not had a chance to diffuse.

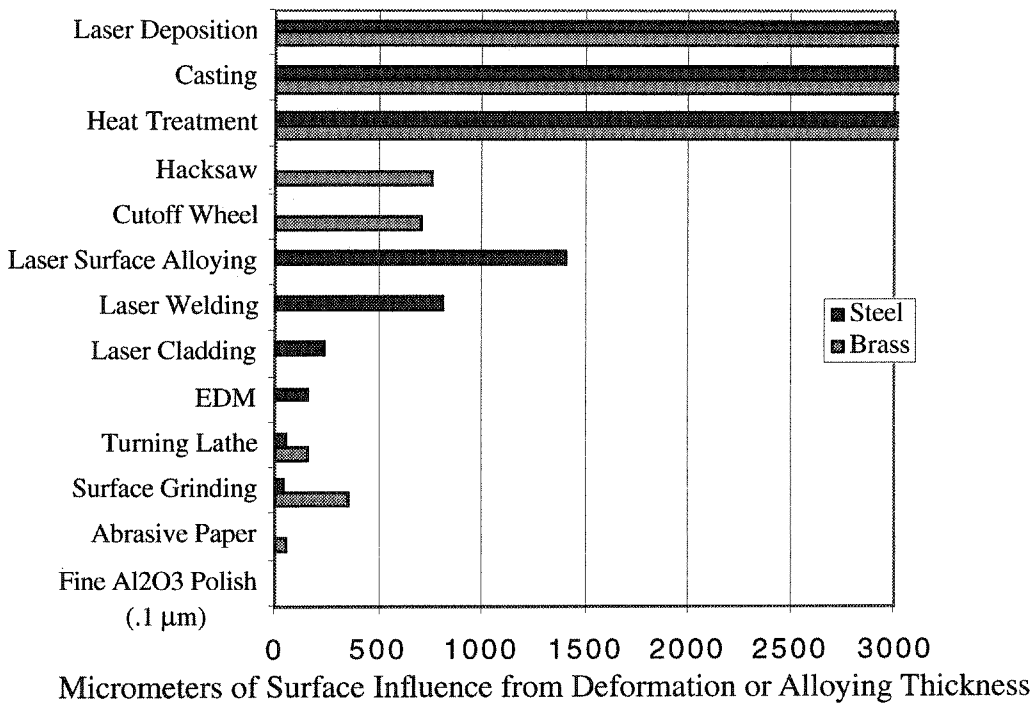

Figure 1. Aggregate Vs. Local Influence on a parts microstructure. Compiled from [1,2,4,5]

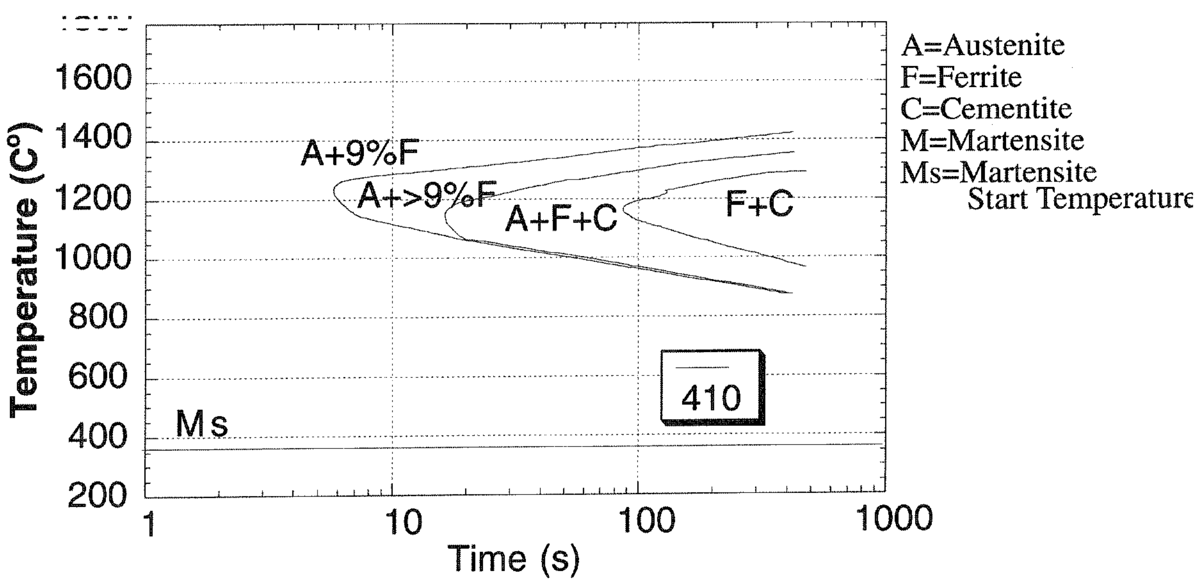

Figure 2. Isothermal Transformation Diagram of 410 steels. Compiled from [7].

This transformation results in an expansion in volume. This expansion can be as big as 4%. This is the same order of magnitude as the thermal shrinkage which arises from cooling of the metal. If martensite transformation can be induced and controlled by layered laser deposition, then the potential to balance the solidification shrinkage with phase volumetric expansion may exist.

The use of lasers to change part or surface microstructure has been extensively researched for laser cladding and surface hardening. Several researchers have shown a relationship between laser parameters and microstructual evolution for laser cladding and surfacing. Wang et al. [3] showed that metastable phases can be produced on material surfaces by laser quenching, a process in which laser melting and quenching of a material occurs by using a very short laser pulses. Yang et. al. [4] used a CO2 laser to show that case depth or the depth of phase transformation and morphology of materials can be influenced by laser power and laser scan rate. Fouquet et. al [5] used a continuous wave CO_2 laser to transform the surface of grey cast iron from austenite to a mixture of austenite, cementite and martensite by using overlapping multiple laser scan paths. Rieker, et. al [6] uses a remelting second pass of the laser to homogenize the chemistry and microstructure of a laser hardened surface on ferritic stainless steel.

2. Experimentation

Experiments were performed to determine the influence on martensitic phase percentage on deformation. Using the SDM lasing technique [8,9], beams were laser deposited using the 400 series martensitic stainless steels. This technique uses a 2.4KW Nd:YAG continuous wave laser whose fiber optic is mounted on a robot which is used for 3D translation. Only additive processes were used to build test beams. Table1 shows the chemical composition of the steels used. A 127 mm x 6 mm x 12.5 mm beam was deposited in 5 layers on substrates which were 152.4 mm x 6.25 mm x 25.4 mm in size. Substrates were annealed to 74 Rb (HK). Beams were built in single pass or double pass configuration. Single pass (SP) allowed for the powder material to melt and fuse upon the substrate or previously deposited layer. Double pass (DP) allowed for one laser scan to melt and fuse the powdered material while a second scan remelted and heated the newly deposited layer without the addition of any new material. The second pass occurred within seconds of the completion of the first at the same scanning speed and power. Three to five beams for each material and at each condition, single pass or double pass, were built. The deflection of the beams was measured using coordinate measurement machine in a process similar to measuring warp in silicon wafers (ASTM F657-1992). Microhardness testing was also performed on cross sections of the beams.

The cross sections were repolished and etched with solutions which leave colored films upon individual phases of the materials [10]. Phase percentages were determined by a color metallography analysis program called "Blue." Metallographic RGB color standards are determined for each phase of a particular material. Blue uses a polygonal RGB pixel value matching algorithm to isolate phase regions. The program matches RGB pixel values with a region in RGB color space and can automatically isolate different material phases. Blue when tested with known phase percentage color metallographs was within 3% of those values and was within 4% of X ray diffraction SDM tool steel samples [10, 11]. This produces an accuracy comparable to manual assessment using ASTM Standard E45-1997 and E1268-1994. Over 3000 metallographs were analyzed using this method. Transmission electron microscopy was also used to analyze material phases following the indexing procedure described by Williams and Carter[12]. Picral pre-etches were used with sodium metabisulfite to reveal as-quenched martensite (M_{AQ}). Hydrochloric acid plus nitric acid and sodium thiosulfite etches were used to reveal tempered martensite. Klemm's reagent was used to reveal ferrite. Table 1 is a list of the materials compositions tested.

Table 1: Test Material Composition

	C%	Mn%	Si%	Cr%	Ni%	Mo%	Nb%	Al%	P%	S%
410	.06	.17	.53	12.5	.07	0	0	0	.017	.007
420	.45	.49	.54	13.6	0	0	0	0	.017	.007
431	.18	.69	.57	15.6	1.78	0	0	0	.016	.003
SDM Tool Steel	.01	1	1.23	21.5	2.8	0	.84	0	0	0
316L	.02	1.74	.73	17.3	13.1	2.66	0	0	0	0

3. Results

Once the deposition of the beams was completed, the beams were tested for deflection and phase composition. Table 2 lists the average results for each type of material tested.

Table 2: Results of Deposition Experiments

	Laser Pass	Deflection (mm)	% As-quenched Martensite (M_{AQ})	% Tempered Martensite (M_T)	% Austenite	% Ferrite	M_{AQ}/M_T
410	1	.97	7	55	36	0	.125
420	1	1.26	19	74	3	2	.249

	Laser Pass	Deflection (mm)	% As-quenched Martensite (M_{AQ})	% Tempered Martensite (M_T)	% Austenite	% Ferrite	M_{AQ}/M_T
431	1	.432	29	62	4	0	.471
SDM -Tool	1	.89	9	68	21	0	.129
316L	1	.97	0	0	98	0	.0
410	2	1.14	4	88	6	0	.047
420	2	.33	29	58	10	0	.506
431	2	.33	32	63	5	2	.51

Selective etchants revealed martensitic and austenitic phases in all the metals with the exception of 316L which is only austenitic. Martensitic stainless steel, 420, had three phases: austenite, martensite, and ferrite (Figure 3 and Figure 4).

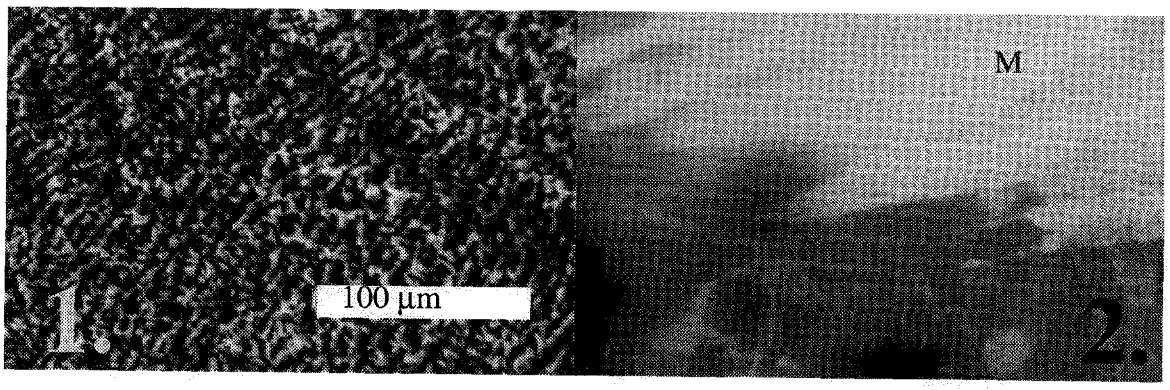

Figure 3. Pictures of 431 stainless: 1. Optical microscope with light brown reflecting tempered martensite, black - as-quenched martensite, white - retained austenite. 2. Brightfield image of TEM with white regions - martensite, black regions - austenite. @30,700 X.

Microhardness for the specimens ranged between 400-540 HK. For each of the metals, the hardness ranges were typically below the value of typical as-quenched or hardened steel ranges. The reheating affect of subsequent layer deposition or the retention of softer phases like austenite could cause this reduction in hardness. Figure 5 compares the quench/hardness ranges for the martensitic stainless steels used in the experiments.

For certain materials increasing the martensite percentage reduced deflection while it increased it in others. Figure 6 shows that by increasing the ratio of as-quenched martensite to tempered martensite, deflection is reduced.

More as-quenched martensite is found in base layers than in N+1 layers (middle and top layers). This suggests that the quenching rate is much faster near the substrate than for subsequent layers. The double laser pass condition increases the quenching rate for middle sections of the beams than the single pass condition. The inset in figure 6 compares middle and bottom layers of 420 in single pass and double pass condition.

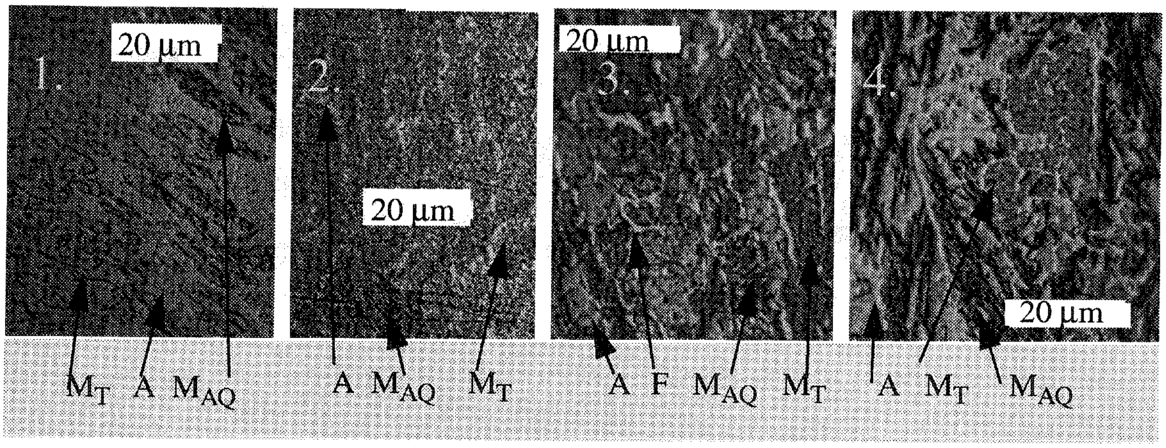

Figure 4. Optical Microscope pictures of :1. 410 - SP, 2. 410 - DP, 3. 420 - SP, 4. 420 - DP.

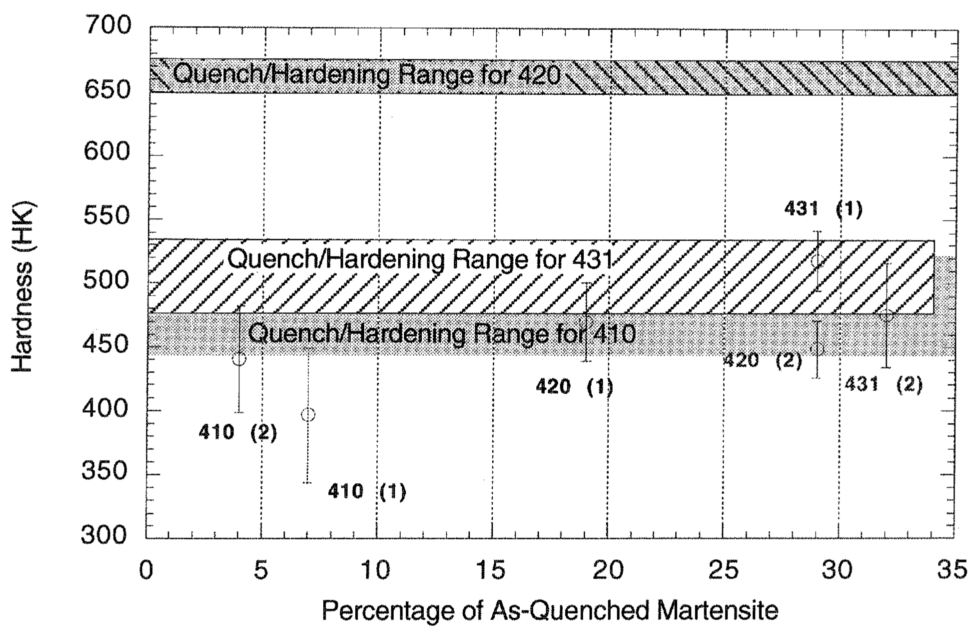

Figure 5. Comparison of the hardness values for martensitic stainless steel beams: 1 - Single Pass, 2- Double Pass. Quenching range compiled from [13].

4. Discussion

Increasing the amount of as-quenched martensite retained in the beams reduced the deflection of SDM deposited beams. As-quenched martensite allowed for maximum volumetric expansion. Tempered martensite allowed the carbon to diffuse, shrinking the lattice and reducing the amount of volumetric expansion achieved. SDM laser manufacturing induced as-quenched martensite. However, reheating of layers during the deposition of subsequent layers tempered much of the as-quenched martensite. The addition of a second laser pass increased the quenching rate and helped maintain more as-quenched martensite for most of the metals tested. Attaining a ratio of at least .45 as-quenched to tempered martensite produced a 30-75% reduction in deformation in the SDM deposited beams.

These tests upon the SDM layered process indicate that continuous deposition of material layers influences the microstructure of N, N-1, N+1 layers. The layer that is being deposited, N, is obviously affected because of the melting and solidifying of the material. The N-1 microstructure is affected because of the reheating of the layer due to the newly deposited layer. The next layer, N+1 is affected because its grain growth direction is seeded from the prior layer N. As more layers are deposited, more heat is retained in the bulk. Grain growth in both austenitic and martensitic steels increases with each additional layer. Grain size in layer N+1 is larger than in N. However, in martensitic steels, this increased heat retention produces more tempered martensite in the bulk and upper layers than near the interface between substrate and first layer. The difference in the heat characteristics is an important element to modelling and understanding the phase development within layered metal parts.

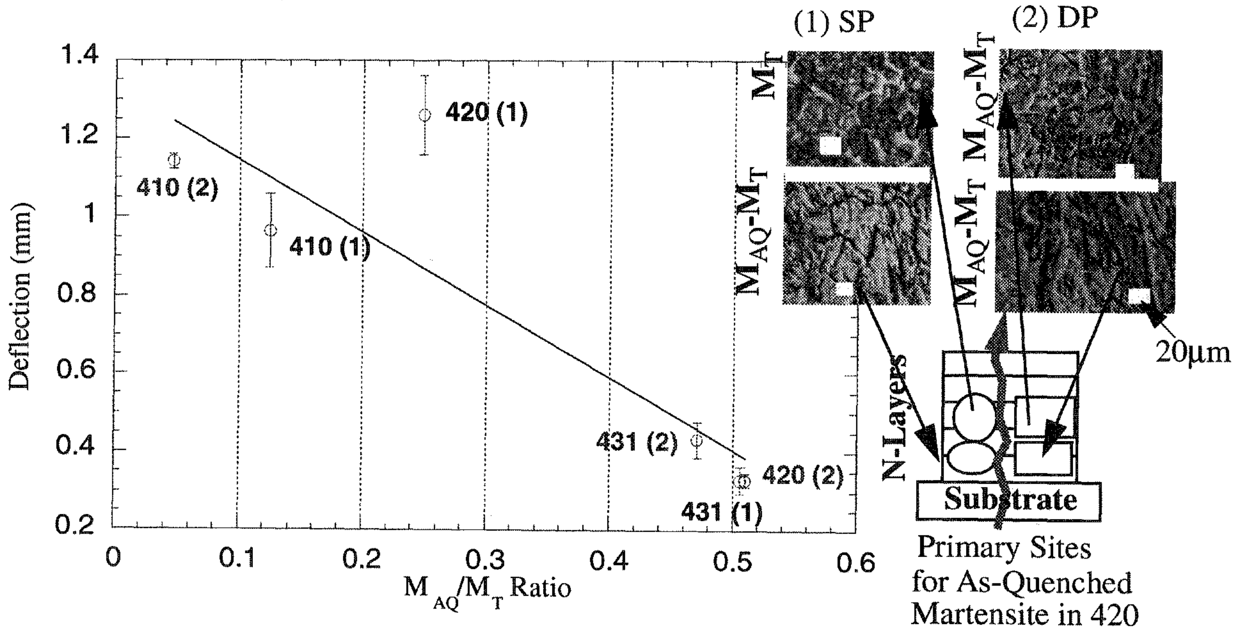

Figure 6. The effect of increasing M_{AQ}/M_T Ratio on deflection.

Multiple phases may be both detrimental and beneficial to material properties. A fully martensitic beam that is in the as-quenched phase may be too brittle to use. A beam that has ferritic phases could develop sigma ferrite which is a brittle phase often related to crack initiation points in metal. However, the retention of austenite or delta ferrite has been shown to increase the toughness of martensitic parts [14]. Because of increased material toughness, prototype die inserts may be a promising use of this technology. Characterizing phase development in layered laser deposition will be one of the keys to reducing part deformation.

5. Conclusion

Solid Freeform Fabrication metal parts are disposed to failure from deformation caused by material responses to large temperature gradients and cooling rates. Deformation can be controlled with special fabrication strategies and heat treatment but with a trade-off of increased build time and finishing operations. However, laser layered manufacturing of carbon steels parts produces martensitic phase transformation which causes volumetric expansion, which has the potential to reduce or eliminate part deformation. Planar beams built by SDM technology significantly reduced deformation by inducing an as-quenched to tempered martensite ratio of .45 or higher.

6. References

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