Nickel Applied for Selective Laser Sintering Using a Magnetic Field

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Abstract

Metal powder was applied for the Selective Laser Sintering process using the sieve feed system and a magnetic field. The magnetic field had a negative effect on final part quality as measured by a reduction in final part density. This negative effect is theorized to be due to the shape and orientation of the magnetic field. It appears possible to change the field to a benevolent orientation.

Introduction

Selective Laser Sintering is proceeding into direct metal sintering. One problem encountered in this process is powder bed packing. Magnetic fields have been used in an attempt to improve the powder packing characteristics of ferromagnetic powders.

The magnetic field hypothesis, which states that magnetostatic application of powder with the sieve feed system will improve part quality over that of the sieve feed system by itself, has been developed to guide this analysis. Three different nickel experiments were performed to test this hypothesis: a single layer nickel experiment, a multiple layer nickel experiment, and a multiple layer nickel experiment where nickel powder is applied with the magnetic field off.

Experimental Procedures

This work was performed on the Intermediate Temperature Workstation located in the Balcones Research Center at the University of Texas at Austin. The work station was equipped with an Nd:Yag laser with a maximum power output of 68 Watts. Single layer nickel powder was applied by placing powder on the top of the part cylinder and leveling it with a scrapper. The cylinder had an electromagnet placed in it, and the powder was placed on top of the magnet as depicted in Figure 1, below. The powder depth was three millimeters so powder was left between the part and the top of magnet after sintering. Each test consisted of three parts 20 mm square.

During powder application, some powder would fall between the top of the solenoid and the part cylinder walls and become trapped around the solenoid bottom. Before a magnetic test was made, the magnet had to be extracted, and the trapped powder removed. If the trapped powder was not removed, a drastic drop in magnetic flux was observed.

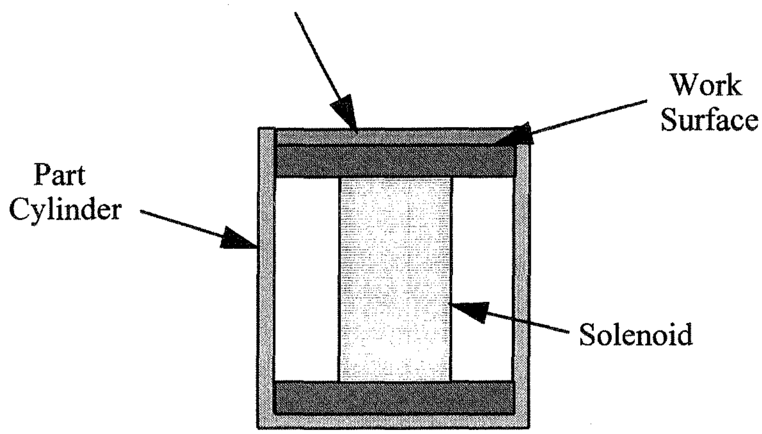
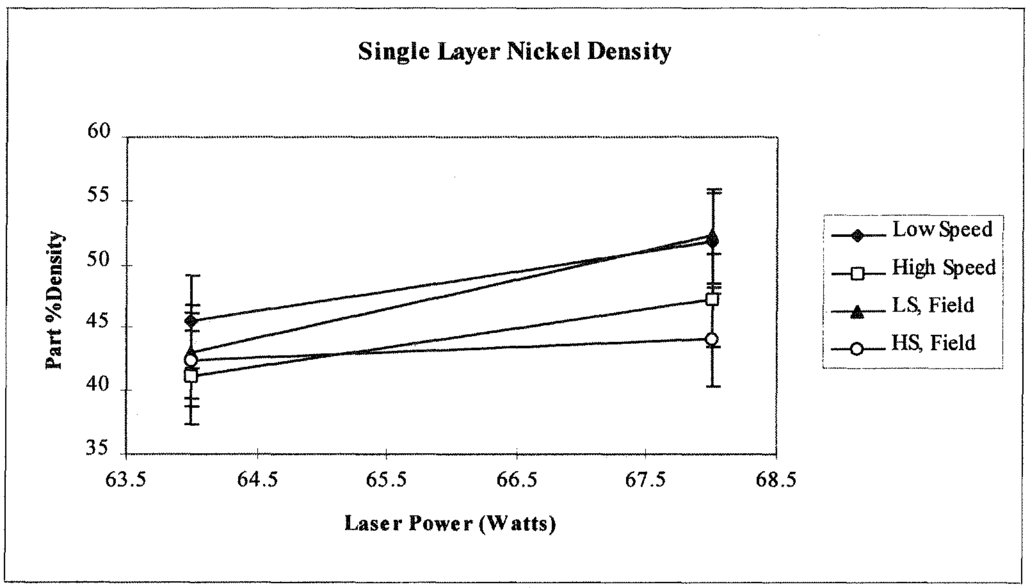


Figure 1
Magnetic Coil in Part Cylinder



Graph 1
Single Layer Nickel Density Plotted vs. Laser Power

Single Layer Nickel Experiment

The single layer nickel experiment was a calibration experiment used to determine the best parameters for future nickel experiments. The magnetic experiment varied the scan speed (0.24 m/s, 0.16m/s), laser power (59 W, 68 W), and magnetic field (0 G, 60 G). The powder bed was allowed to sit in a standard laboratory nitrogen environment for ten minutes to remove help remove residual oxygen from the powder before sintering. The experiment consisted of 16 runs of three parts each for a total of 48 parts.

Data gathered in the single layer nickel experiments is presented in Graph 1 above. ANOVA analysis showed a noisy, but statistically significant experiment in the 95% confidence interval. The analysis of this experiment shows that 54.33% of variation about the mean was due to laser power, 31.57% was due to laser speed, and 14.09% was due to error. The magnetic field and all interactions were statistically insignificant. Therefore, the magnetic field does not affect the part density.

All nickel parts produced in single layers, or subsequently in multiple layers, were comprised of sintered balls of nickel. This effect means the parts are formed from a group of spheres with small inter-ball connections at their contact points. They were also normally poor quality parts.

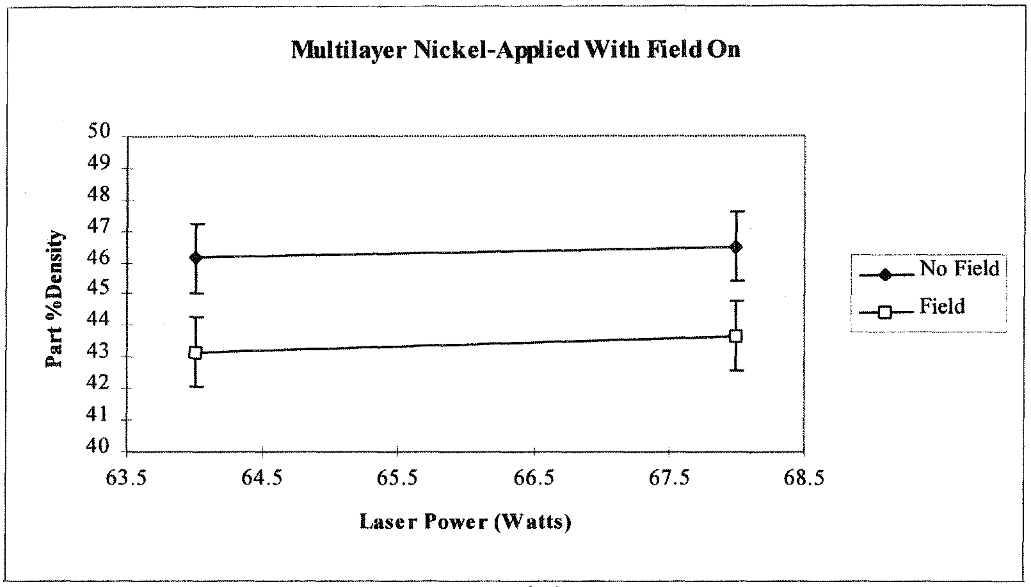
Multiple Layer Nickel Experiments

The multilayer nickel parts were run in a similar fashion to the single layer nickel parts. However, due to a phenomenon observed during the tests, two separate experiments were performed in the multilayer format. Both experiments consisted of three nickel powder layers with the second and third layers applied using the sieve feed system. The experiments were different due to the state of the magnetic field during the powder application phase of the process. The first experiment used the field during powder application, while the second experiment had the field off only during the powder application phase. The field was on during the rest of the processes in both cases, and the cases were the same in all other respects.

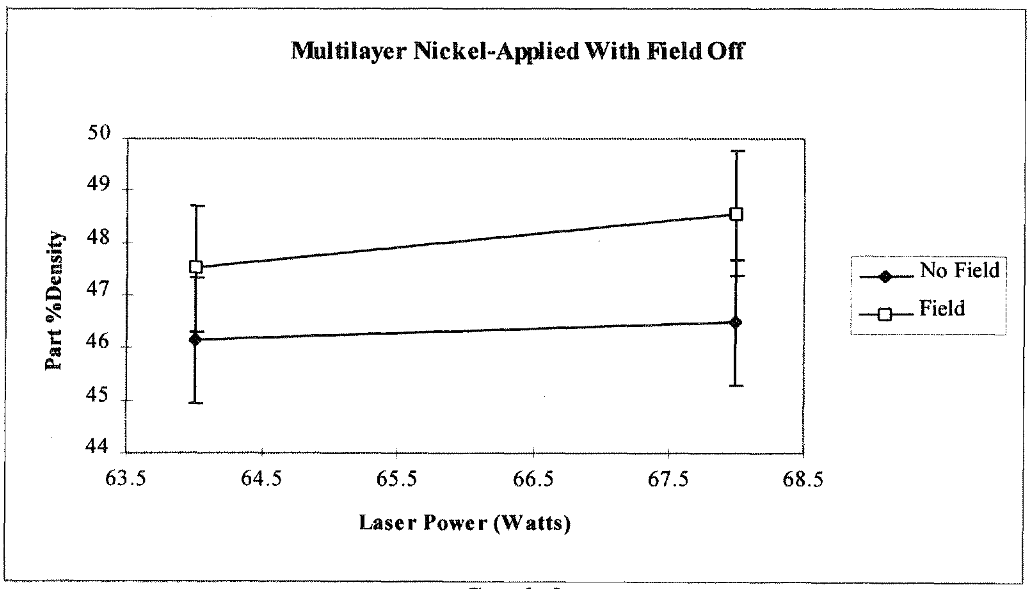
The multilayer nickel parts could not be sintered under the nitrogen environment employed in the single layer nickel experiments. When this was attempted, the parts formed three delaminated single layer parts on top of each other. A very slight amount of particle interaction between layers was noticed in some cases. In order for the parts to be sintered in fastened multilayer parts, forming gas had to be used during the sintering and powder application processes. The forming gas consisted of 4% hydrogen and 96% nitrogen. After the powder was applied and leveled for the first layer, the sieve and powder to be used for the second and third part layers were placed in the chamber. The chamber was then sealed and the powder was allowed to sit for ten minutes under forming gas before the first layer was sintered. After the second and third layers were applied, the bed was allowed to sit for two minutes before the powder was sintered.

Both of the multilayer experiments varied laser power (64 W, 68 W) and magnetic field (0 G, 60 G) while holding the scan speed constant (0.16 m/s). Each experiment consisted of eight runs of three parts each for a total of 24 parts per experiment. These experiments were performed at room temperature.

The multiple layer nickel experiments presented in Graph 2 below were found to be statistically significant in the 92% confidence interval using ANOVA techniques. The statistical analysis of the experiments shows a statistically significant negative contribution from the magnetic field on the part density. This result may be due to the observed fact that particles from the second and third powder layers applied by the sieve stand up on end along magnetic field lines when they are delivered from the sieve with a magnetic field.



Graph 2
Multilayer Nickel Data Plotted vs. Laser Power



Graph 3
Multilayer Nickel Applied With the Magnetic Field Disengaged Density Data Plotted vs. Laser Power. The Experiment is Statistically Insignificant.

The multilayer nickel experiment with the magnetic field turned off during powder application, presented in Graph 3 above, has a confidence interval of 73%. While this experiment is considered statistically insignificant and invalid for this study, it is still important to observe that the magnetic field appears to make a positive contribution to improving the final part density.

Experimental Analysis

The magnetic field hypothesis has been rejected. The single layer nickel and multilayer nickel experiments are the only experiments that were reliable enough to analyze the magnetic field hypothesis. The single layer nickel experiment demonstrated the magnetic field had no effect on part sintering, while the multilayer nickel experiments demonstrated the magnetic field effect was detrimental to final part density. The nickel tests in which powder was applied with the magnetic field off are beyond the acceptable level of confidence, but they do demonstrate the magnetic field helping the system when it is applied only during sintering.

A possible reason that a magnetic field is detrimental to the Selective Laser Sintering process during the powder application phase was noticed during the experiments. When the powder is applied from the sieve with a magnetic field, the powder is observed standing up along magnetic field lines. This observation leads to the conclusion that the magnetic field visibly reduced the packing of the powder bed. Additionally, this observation was the reason for experiments in which the powder was applied without a magnetic field. The tests of powder applied without a magnetic field imply the magnetic field may possibly help the part quality by affecting sintering, although no definite conclusions may be drawn from these experiments due to statistical insignificance.

The use of the magnetic field necessitates only minimal preheat ($\approx$250°C for nickel) may be used during the Selective Laser Sintering process. The Curie point of nickel is 335°C [Callister p. 517], while the melting point is 1453°C [Callister p. 554]. The maximum temperature at which there is still half the maximum saturation magnetization is $\approx$250°C for nickel. These saturation points and Curie points will be surpassed if the normally desired green bed preheats of 950°C or higher are used in the direct metal sintering process. Once these temperatures are surpassed, the materials will no longer be ferromagnetic, rendering the fields ineffective.

Preheat is utilized to alleviate curl, help remove water and oxides, and to reduce laser power. Therefore, if a magnetic field is to be used in the Selective Laser Sintering processing of ferromagnetic metal, then the magnetic field must replace the preheat's functions and improve final part quality. The magnetic field does not improve final part quality within this criterion, and thus even in the insignificant cases where the magnetic field helped sintering, it is still a negative result, because it did not replace the function of the preheat.

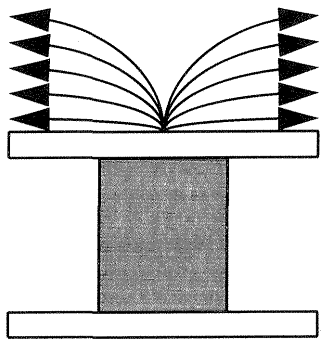


Figure 2
Exaggerated Magnetic Field Lines of Workplate Magnet

Theoretical Analysis

The theoretical mechanisms involved in the disruption of part quality under a magnetic field may be observed visually, as described previously. This same mechanism theoretically may be used to increase the bed density if it could be decoupled from the harmful magnetic effects.

Figure 2 above depicts exaggerated lines of constant magnetic field strength for a solenoid similar to the one used in the Intermediate Temperature Workstation during the magnetic field experiments. In an ideal case, all of the field lines would be vertical and emanate from the center of the solenoid. Realistically, however, the edge effects dominate and cause the field lines to bend and eventually return to the bottom of the solenoid.

The observed particles, which are nonuniform, in the magnetic experiments have aligned themselves along these lines of constant magnetic field. This occurs because the particles conduct the magnetic field better than the ambient air. In doing so, the particles in the center are forced to stand up on end to create the longest path of least resistance for the magnetic field. Also, since the particles are a better conductor of this field than air, the field is stronger when it travels through a particle instead of air [Rao p. 244]. Once these particles are standing on end and a particle is applied from the sieve, dropping through air to the workplate, it is attracted to the strongest field line. These lines are at the end of the particles standing on end, so the incoming particle will be attracted to the end of a standing particle. In this fashion, particles align along the field lines, and the green bed density is corrupted to a point where the disruption may be observed visually. When the field is turned on after the powder bed has been applied, the particles still stand up, but only the ones in the very center of the solenoid, causing fewer particles to stand on top of each other. During the experiments, this region was small enough that a part was not sintered in it when powder was applied with the magnetic field off.

Due to edge effects, there are forces on the particles in the vertical direction that cause the particles to stand up, but there also are forces in the radial direction. The forces in the radial direction may be beneficial to the green bed density, because they are capable of causing the particles to be pulled into the center of the solenoid. The radial forces appear to dominate away from the center of where the magnetic field lines have bent back toward the bottom of the solenoid, thus creating a field gradient [Chikazumi p. 5] that can impart a force upon the particles.

The radial forces are theorized to pull particles toward the center of the solenoid, resulting in a compaction of the green powder bed that should lead to an increase in density of the green powder bed. Unfortunately, this radial force is removed from the individual particle during sintering, because the metal powder increases in temperature to the molten phase, well above the Curie point of the material. However, because the material is in a powder bed, some compaction force will still be present. Particles that are further out from the center of the solenoid will still be exposed to a radial force, and thus could push the particles being sintered toward the center of the solenoid, resulting in a compaction in the radial direction of the heated particle during particle sintering. This process is illustrated in Figure 4. Also, during sintering, the vertical force is eliminated from the individual particles because the material is above its Curie point.

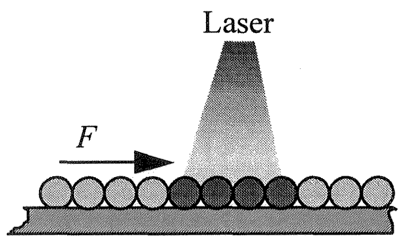


Figure 4
Radial Force on Sintering Particles

A radial compaction force could help to densify the green powder bed. However, a vertical force seems to inhibit powder bed packing. From the experiments, it is known conclusively that particles which are applied with the magnetic field on produce poorer quality parts than those sintered without a field. This implies that vertical forces dominate the powder bed packing properties. However, in cases where the powder was applied with the magnetic field off, but sintered with it on, it has been inconclusively determined that the field provides some help, implying that radial forces may dominate the powder bed packing characteristics. It therefore may be possible to increase green powder bed density with a magnetic field as long as the part is not fabricated in the center of the solenoid where vertical forces dominate. However, the increase in part quality from the magnetic field will be negligible compared to that from preheating the powder bed to a point above the Curie temperature.

Conclusions

The magnetic field hypothesis which states that magnetostatic application of powder with the sieve feed system will improve part quality over that of the sieve feed system by itself, has been rejected. It is rejected because the magnetic field does not help final part quality as much as preheating the powder bed does. It is also only rejected for this experiment, as it may be possible to shape the magnetic field in a manner that could help the final part quality.

The mechanism of failure in this hypothesis appears to be the particle alignment phenomenon. It appears the magnetic field causes particles to stand up thereby reducing green bed density. It is also theoretically possible that a magnetic field designed to pull powder particles toward the center of the workplate could help the final part quality. However, the application of a magnetic field must compensate for a reduction in powder bed preheat necessary to allow ferromagnetic interaction.

Sources

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