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Selective laser melting of soft magnetic alloys for automotive applications

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Abstract
Selective laser melting is a powder-bed fusion additive manufacturing process that offers a high degree of freedom in material development and design optimization in the automotive industry. This paper investigates the use of selective laser melting of soft magnetic alloys in producing electrical motors for gas-electric hybrid and fully-electric vehicles. Additive manufacturing of soft magnetic alloys is proposed as an innovative manufacturing method that allows producing new motor designs and enhances the magnetic and thermal properties of electrical motors. The feedstock material is gas-atomized metal powder in the size range of 15µm to 45µm. Three soft magnetic alloys, stainless steel 430L, Fe50Ni, and Fe6Si are compared. The density, microstructure, magnetic properties, and electrical properties of the three alloys are studied. Selective laser melting could be associated with void formation, internal cracks, vaporization of alloying elements, and residual stresses. Hence, an optimum process window is evaluated for each material to minimize the process flaws. The optimum process parameters are utilized to produce motor stators from each material. The magnetic and electrical performance of the motors produced is analyzed. The performance of the additively manufactured motors is compared with that of the traditional motors.

Mechanical, Metal, Microstructure, Selective laser melting (SLM)

1. Introduction and background

Additive manufacturing (AM) allows manufacturers to implement design optimization and material development in the automotive industry for shortening the development cycle and reducing the manufacturing and product costs. Selective laser melting (SLM) is a laser powder bed fusion (L-PBF) process that allows producing complex parts and structures using newly developed materials [1]. This paper investigates the use of SLM for processing three soft magnetic alloys for applications that require high permeability and high magnetic performance (e.g., electrical motors). Stainless steel 430L exhibits high corrosion resistance due to its high chromium content [2], Fe50Ni exhibits very high permeability and low core loss due to its high nickel content [3], and Fe6Si reveals low core loss and brittle fracture due to its high silicon content [4]. The three soft magnetic alloys are hard-to-machine but weldable.

The typical properties of soft magnetic alloys include, but not limited to, high permeability, high saturation magnetization, low core loss, low eddy-current loss, and low coercivity [5]. A few studies have been reported in the open literature for laser AM of soft magnetic alloys. A study showed that the mechanical and magnetic properties of iron-cobalt soft magnetic alloys produced using SLM are in line with those of the wrought materials [1]. Another study showed that the magnetic properties of iron-cobalt soft magnetic alloys could be improved via heat treatment after L-PBF [6]. Soft magnetic alloys include iron-nickel alloys, iron-silicon alloys, iron-cobalt alloys, low carbon steels, ferritic steels, and soft magnetic amorphous alloys [7]. In the current study, the SLM of low carbon steels (e.g., stainless steel 430L), iron-nickel alloys (e.g., Fe50Ni), and iron-silicon alloys (e.g., Fe6Si) was explored. The properties of the as-built parts were compared.

2. Experimental work

The SLM process is associated with void formation, internal cracks, vaporization of alloying elements, and residual thermal stresses [8-15]. In order to eliminate these flaws and defects, an optimum process window should be defined for each new material in SLM [11, 16, 17]. The SLM main process parameters include laser power P in (W), scanning speed v in (mm/s), hatch spacing h in (mm), layer thickness t in (mm), stripe width w in (mm), stripe overlap δ in (mm), scanning strategy, and contouring [8, 11, 15-18]. A process window of laser power, scanning speed, and hatch spacing was determined in this study.

2.1. Feedstock materials

Three gas-atomized soft magnetic powders were considered in this study. Table 1 shows the material composition of stainless steel 430L, Fe50Ni, and Fe6Si powders, supplied by Sandvik Osprey LTD. The powders were identical spherical particles in the size range of 15-45 µm and were sieved before the SLM process via a 200-mesh sieve (75 µm).

Table 1 Material composition of soft magnetic alloys (wt.%)

	Stainless steel 430L	**Fe50Ni**	**Fe6Si**
Fe	Balance	Balance	Balance
Ni	-	48-50	-
Cr	16-18	-	-
Si	1	0.25	5-7
Mn	1	0.50	-
C	0.03	-	-
P	0.04	-	-
S	0.03	-	-

2.2. Experiments and equipment

The current study covers two main experiments: (i) producing cubes with an edge length of 10 mm from each material, and (ii) producing electric stators from each material. The first experiment is aimed at finding the optimum SLM process parameters for each soft magnetic alloy, and the second experiment is aimed at producing motor stators using the optimum SLM process parameters. An EOSINT M280 SLM machine and nitrogen gas flow were used.

2.2.1. Optimization of SLM process parameters

Three SLM process parameters (i.e., factors) were optimized for part density based on a full factorial design of experiments (DOE). Three levels were selected for each factor, as illustrated in Table 2. The DOE included 27 runs ($\text{levels}^{\text{factors}} = 3^3 = 27$ runs). The constant parameters are presented in Table 3. Each experimental run was used for producing a cube with an edge length of 10 mm from each material, which means a total of 27 cubes were produced in the same build plate for each material. No post-processing procedures were performed on the parts produced. The samples were removed from the build plate using wire electrical discharge machining (EDM).

The density of the cubes was measured at ambient temperature using the Archimedes method [15, 19]. Based on the density results, the optimum SLM process parameters were determined for each material. By using these optimum process conditions, dense parts could be produced with no void formation and/or alloying element vaporization.

Table 2 Design of experiments matrix of three factors at three levels

Parameter	Level 1	Level 2	Level 3
P **(W)**	200	250	300
v **(mm/s)**	600	800	1000
h **(mm)**	0.08	0.10	0.12

Table 3 Design of experiments matrix of three factors at three levels

Parameter	Value
Layer thickness t	0.04 mm
Stripe width w	10 mm
Stripe overlap δ	0.08 mm
Scanning rotation between layers	67°
Scanning strategy	Stripe scanning
Contouring, up-skin, and down-skin	Deactivated

2.2.2. Producing electric stators

The optimum SLM process parameters were used for producing motor stators, shown in Figure 1, from each soft magnetic alloy. The height of each stator was 18 mm after removing the build plate (i.e., extra height was added to allow for wire EDM).

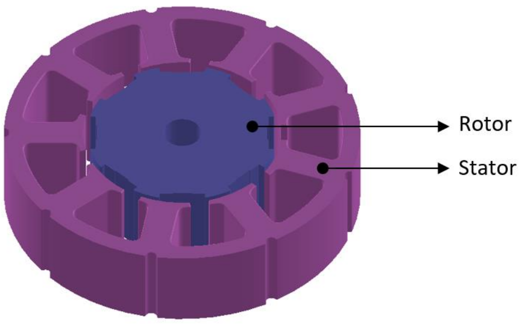

Figure 1. Illustration of motor laminations (rotor and stator)

3. Results and discussion

For each experimental run, the volumetric laser energy density was calculated using Equation (1), where v is average scanning speed in (mm/s), P is laser power in (W), h is hatch spacing in (mm), t is layer thickness in (mm), and E_v is volumetric laser energy density in (J/mm^3).

$$E_v = \frac{P}{v \times h \times t} \tag{1}$$

3.1. Density results

The relationship between the laser energy density and the relative density of parts produced was studied for each material, as shown in Figure 2. The density measurements showed that the laser energy density has a strong influence on the relative density of parts produced. It was found that parts produced using any combination of process parameters that gives low laser energy density have low density due to void formation. However, very high laser energy density leads also to low density due to the vaporization of some of the alloying elements.

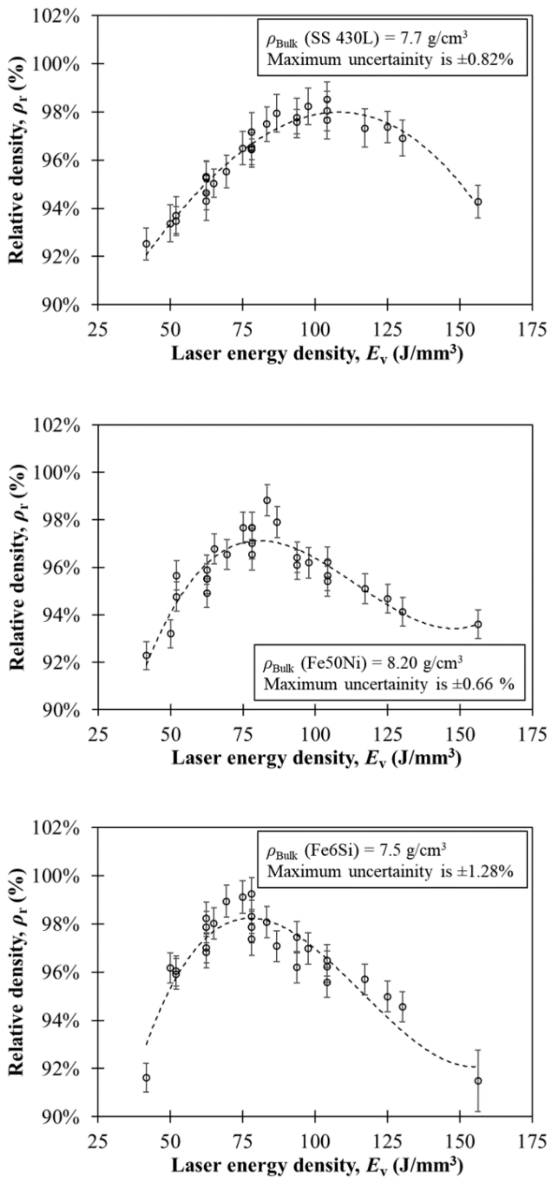

Figure 2. Relative density of stainless steel 430L (SS 430L), Fe50Ni, and Fe6Si cubes produced using SLM

Density results showed that the full melting of stainless steel 430L, Fe50Ni, and Fe6Si require laser process parameters that give laser energy density of 104.2 J/mm^3, 83.3 J/mm^3, and 78.1 J/mm^3, respectively. Table 4 shows the optimum SLM process parameters for each soft magnetic alloy.

Table 4 Optimum laser process parameters for each soft magnetic alloy

	Stainless steel 430L	Fe50Ni	Fe6Si
P **(W)**	200	200	200
v **(mm/s)**	600	600	800
h **(mm)**	0.08	0.10	0.08
t **(mm)**	0.04	0.04	0.04
E_V **(J/mm^3)**	104.2	83.3	78.1

3.2. Electrical properties

The optimum SLM process parameters, illustrated in Table 4, were used to produce motor stators from each soft magnetic alloy. The motor components were removed from the build plate using wire EDM. Rotors of electrical steel 50A800 were used, and the magnet material was N42UH. Double strand wire of 1.4 mm diameter was used for winding, as shown in Figure 3.

Figure 3. (a) Front view and (b) top view of stainless steel 430L and Fe50Ni SLM motors after winding

It is worth noting that Fe6Si parts showed small surface cracks due to their brittle behavior. Only stainless steel 430L and Fe50Ni motors were included in the electrical analysis. The SLM motors had no laminations, so a high iron loss was expected. A laminated motor (not additively manufactured) was tested as a reference for comparison. Performance tests were conducted on the motors produced. The electrical resistance in ($\mu\Omega$) and inductance in (μH) were measured for each phase (U-V, U-W, and V-W) of each motor. Table 5 summarizes the results of the SLM motors compared to those of an original motor with laminations. The iron loss in (W) was measured for each motor at various motor speeds in RPM (revolutions per minutes). Figure 4 shows the iron loss curve for each motor (stainless steel 430L, Fe50Ni, and laminated motor). It was found that stainless steel 430L and Fe50Ni motors showed electrical resistance in line with that of the laminated motor. However, the SLM motors showed lower inductance than the laminated motors due to iron loss. Since there were no laminations and isolators in the SLM motors, the iron loss in both motors was very high. Motor inductance is attributed to the magnetic of the electric motor. A reduction in the motor inductance could lead to a voltage drop in the electric motor. It is recommended to produce isolators between layers during the SLM process to increase the inductance of the SLM motors. This could be achieved using a multi-material SLM system which is considered for future work. It is expected that producing isolators between layers would reduce the iron loss, increase the motor inductance, and enhance motor efficiency and performance. The surface roughness of SLM parts could also be a potential source of air friction loss. The surface of the additively manufactured soft magnetic parts could be improved by some post-processing and surface finishing procedures.

Table 5 Electrical properties of the SLM motors compared to the original motor (with lamination)

	Stainless steel 430L	Fe50Ni	Lamination
	Electrical resistance in ($\mu\Omega$)		
U-V	6.60	6.62	6.65
U-W	6.61	6.65	6.60
V-W	6.61	6.63	6.63
	Inductance in (μH)		
U-V	13.0 – 14.4	14.6 – 15.1	29.6 – 34.1
U-W	13.1 – 14.6	14.4 – 15.4	29.0 – 34.2
V-W	13.0 – 14.2	14.5 – 15.5	29.4 – 33.9

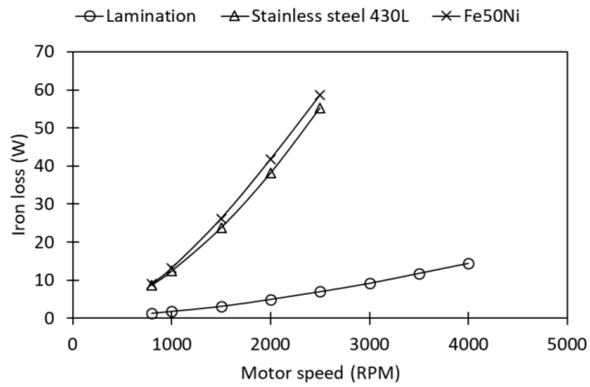

Figure 4. Iron loss of SLM motors compared to an original motor with lamination

4. Conclusions

This paper dealt with the selective laser melting of soft magnetic alloys. Three soft magnetic alloys were considered for this study: stainless steel 430L, Fe50Ni, and Fe6Si. Optimum laser process parameters were determined for each material. These optimum parameters were used to produce motor stators with no isolators for testing. The electrical resistance, motor inductance, and iron loss were measured for each motor. The results of the SLM motors were compared with those of an original motor with laminations and isolators.

The electrical resistance of the SLM motors was in line with that of the original laminated motor. The SLM motors showed inductance lower than that of the laminated motor due to iron loss. This could be attributed to the fact that the SLM motors did not have isolators between stator laminations. It was concluded that a multi-material SLM system is required to produce laminations with isolators using soft magnetic alloys. Producing SLM motors using a multi-material SLM system is considered for future work. It is also recommended to study the post-processing and surface finishing of soft magnetic alloys processed via SLM.

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