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Thermal Conductivity of Metal Powder and Consolidated Material fabricated via Selective Laser Melting

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Abstract. Selective Laser Melting (SLM) is a direct fabrication of part through layer by layer powder deposition and successive laser beam irradiation based on Computer Aided Design (CAD) data. One of the important properties in SLM is thermal conductivity of metal powder. This is because the ability of metal powder to conduct heat will affect the consolidation process during SLM. In this paper, thermal conductivity of metal powders with different particle diameters and their mixture was analysed. Other than that, thermal conductivity of consolidated materials fabricated via SLM process was also studied. In order to measure the thermal conductivity of metal powder, a theoretically verified method which was previously developed by the authors was used. Determination of thermal conductivity of consolidated material was analysed using laser flash technique. It was found that the thermal conductivity of powder metal was influenced by bulk density and particle diameter of metal powder. In this study also, metal powders of different particle diameters were mixed with various volume ratios, and its effect was discussed. Thermal conductivity of the consolidated materials was also examined, and its relation to porosity was elaborated.

Introduction

Selective Laser Melting (SLM) is an emerging rapid manufacturing (RM) process that has a high potential for development of functional product. SLM is a direct fabrication of near net shape product that is accomplished through the layered manufacturing system. During SLM process, a thin powder layer is deposited, and laser is irradiated to powder surface successively until final part is produced based on CAD data. The part is a consolidated material where its mechanical properties and appearance are influenced by powder materials and fabrication parameters.

Thermal conductivity is an important thermophysical property in SLM. This is because the ability of metal powder to conduct heat will affect the consolidation process. Thermal conductivity, K is a measure of the rate of heat transfer through material. During SLM, laser beam is irradiated to the powder surface. Before consolidation occurs between powder particles, heat from irradiated powder is conducted to other adjacent powder particles. Good consolidation between metal powders particles occur based on the appropriate amount of heat to melt the powder particles so that it can fuse and form solid with surrounding powder particles. During this consolidation process, heat transfer process occurs through the powder particles and air gap. Therefore, thermal conductivity is an essential element in understanding the consolidation process of metal powders.

In order to determine thermal conductivity of metal powder, there are various techniques such as photoacoustic [1], modified hot wire [2], transient needle probe [3], crenel heating excitation [4] and photopyroelectric techniques [5]. This research used a technique, which was developed by the author [6]. The technique is relatively simple, cost effective and fast but still produced a reliable result.

The mathematical expression of thermal conductivity was theoretically derived and verified by using instantaneous point source of heat [7]. In this technique, time taken to reach the maximum voltage when a heat source exists at a specified distance using a thermocouple concept is measured. Based on this, thermal conductivity of metal powder, K_{powder} can be determined using equation.

$$K_{powder} = \frac{z^2 \rho C_p}{6T_{max}} \quad (1)$$

where z is distance from the powder surface to thermocouple junction, ρ is metal powder bulk density, C_p is specific heat of metal powder, and T_{max} is measured time to maximum voltage point as depicted in Fig. 2. Since K_{powder} is dependent on metal powder bulk density, ρ, the air gap between metal powder particles is already taken into account in determination of thermal conductivity. Based on the assumption made and mathematical derivation, Eq. 1 is only valid if and only if $\Delta t/t_{cp} < 0.1$ and $z/a > 3.87$ are satisfied, where Δt is irradiation time, t_{cp} is heat transfer time from heat source, a is heat source radius and z is distance from the heat source surface. Throughout this experiment, the value was set equal to 4 whereas of $\Delta t/t_{cp}$ was less than 0.1.

Thermal conductivity is important thermophysical properties for various design applications. Current development in mould making shows the potential of consolidated material to be used as injection mould. In mould application, effective heat transfer allows quality moulded parts to be produced. For instance, effective heat removal from a mould cavity in injection moulding process able to reduce the reject caused by burning, warpage and burnmarks in moulded part. Current studies show that there is only limited data on thermal conductivity of consolidated material despite their increasing application in rapid mould manufacturing. According to Danninger [8], availability of engineering data on thermophysical properties of sintered or consolidated steels are scarce and usually not too reliable. Application of a wide variety of consolidated material requires extensive technical information for engineering design. Therefore, in this paper, the thermal conductivity of metal powder and consolidated material and also factors that affects them are discussed.

Experiment

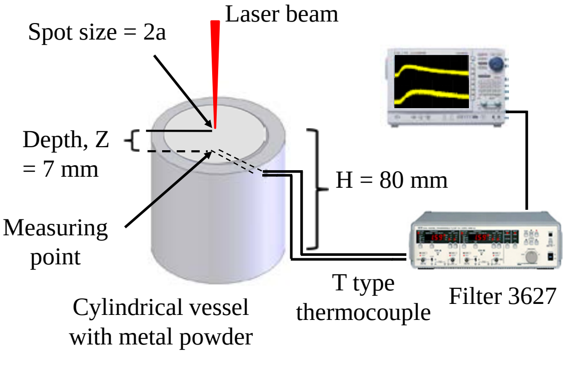

Fig. 1 Experimental setup

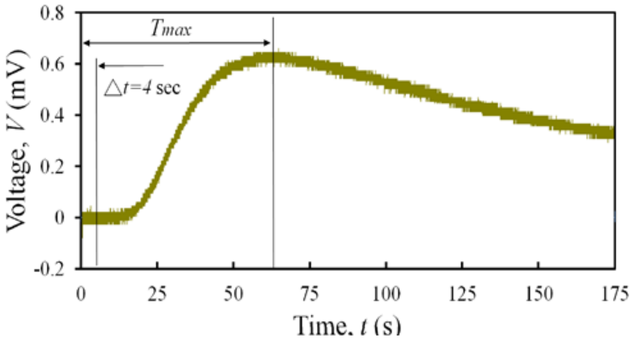

Fig. 2 Oscilloscope output

Thermal Conductivity of Metal Powder. In this experiment, a pulsed type Yb:fiber laser (LP-F10 model) manufactured by SUNX was used to irradiate the laser beam on the metal powder surface. The laser spot size on the metal powder was used as a heat source in thermal conductivity measurement. The experimental setup is shown in Fig. 1. The cylindrical vessel was made from aluminium alloy with outer diameter of 100 mm, inner diameter 80 mm and depth 60 mm. The thermocouple used in the experiment was T type (copper-constantan) with a wire diameter of 0.1 mm and 7 mm distance from top of powder surface. Other conditions set were laser wavelength, λ=1070 nm, spot size, $2a$=2 mm, irradiation time, Δt=4 seconds and irradiation energy, E= 40 J. Fig. 2 indicates common output obtained from thermocouple during thermal conductivity measurement and their nomenclature. T_{max} is measured time to maximum voltage achieved and used to calculate thermal conductivity based on Eq. 1. The specification of the metal powder used as indicated in Table

1. Metal powder used in the experiment was SUS316L with the particle diameter of 10, 20, 50 and 100 micron. Another material used in the study was a mixture of 70% chromium molybdenum steel, 20% copper and 10% nickel (SCM + Cu + Ni) with the particle diameter of 25 micron.

Table 1 Specification of metal powder

Material	Particle diameter, d (µm)	Specific heat, *C* J/(g·K)[9]	Particle shape
SCM + Cu + Ni	25	0.46	Irregular
SUS 316L	10, 20, 50, 100	0.50	Irregular

Thermal Conductivity of Consolidated Metal. Determination of thermal conductivity of consolidated materials was analysed using laser flash technique. In this laser flash experiment, short duration of heat pulse was applied on a surface of 1.5 mm thickness specimen with 8 mm width and 8 mm length. Then temperature change at the opposite surface was the recorded. Thermal conductivity of consolidated materials, $K_{consolidated}$ of the specimens was determined from Eq. 2 where ρ *is* density, C_c was specific heat and α was thermal diffusivity of the consolidated specimen.

$$K_{consolidated} = \rho C_c \alpha \tag{2}$$

Results and Discussion

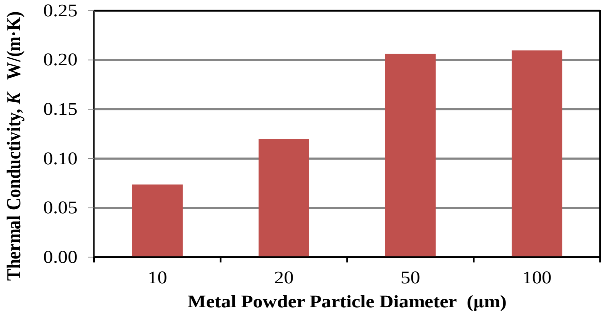

Fig. 3 Effect of particle diameter on thermal conductivity

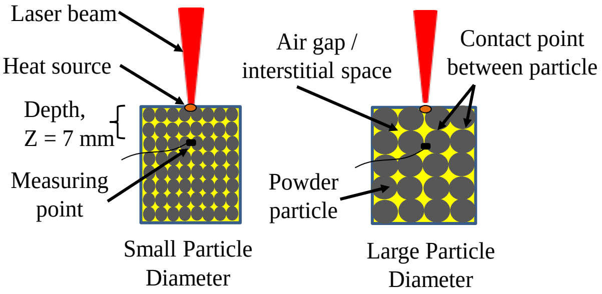

Fig. 4 Comparison of schematic presentation of particle arrangement for different diameter

Effect of Particle Diameter on Thermal Conductivity of Metal Powder. T_{max} recorded for 10, 20, 50 and 100 micron SUS 316 L metal powders was 180.0, 110.6, 59.0 and 51.4 seconds respectively. Thermal conductivity of SUS 316 L metal powders with different particle diameters are shown in Fig. 3. The graph shows that thermal conductivity is increasing with the particle diameter. This behaviour was due to the conductive heat transfer mechanism between powder particles. Fig. 4 shows the comparison of schematic presentation between small and large powder particle inside a cylindrical vessel. As indicated in the figure, there were points where particles were in contact between other powder particles. When the laser beam was irradiated on powder surface, heat was transferred through between these contact points to the measuring point. Since the total air gap per unit area for small and large particle were approximately the same, existence of the air gap between powders was not the main factor that contributed to different thermal conductivity result. Higher heat transfer rate of large powder particle from heat source to measuring point was caused by less resistance experienced by the large particles in comparison to small particles. During heat conduction from heat source to the thermocouple measuring point, small powder particles experienced more repetitive changes between solid and air as a medium. In contrast, for large particle the behaviour is vice versa. Therefore, heat transfer rate of large particle to the measuring point was higher due to less heat loss. As a result, the thermal conductivity of large particle is higher.

Effect of Bulk Density on Thermal Conductivity. In order to investigate the effect of bulk density on thermal conductivity, the surface of metal powder inside the cylindrical vessel was manually compressed and similar experimental setup as shown in Fig. 1 was repeated with different bulk density. The result in Fig. 5 shows the effect of bulk density of metal powder on thermal conductivity. The graph shows that the thermal conductivity of the metal powder is increasing with bulk density. This might be explained by referring to Fig. 6, which shows schematic particle arrangement of the powder particle during the experiment. When metal powder was compressed, the air gap between powder particles was displaced due to external force exerted during compression. Thus, more particles can be added to cylindrical vessel and the bulk density of metal powder was increased. At high bulk density, contact points between powder particles improved since more powder particles were touching with their neighbouring particles. Therefore, more effective heat transfer from the heat source to the thermocouple measuring point occurred. As a result, conductive heat mechanism between powder particles was more prevalent in the higher bulk density powder.

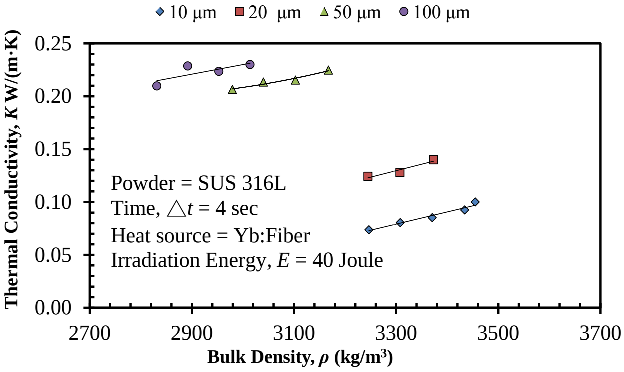

Fig. 5 Effect of bulk density on thermal conductivity

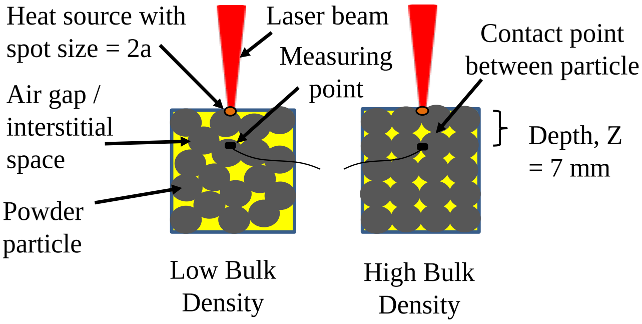

Fig. 6 Comparison of schematic presentation of particle arrangement in different bulk density

Effect of Mixed Powder on Thermal Conductivity. In order to study the effect of mixed powder on thermal conductivity, powders with different particle diameters were mixed with predetermined volume percentage. The mixed powder combination is as tabulated in Table 2. Volume percentage of P1 and P2 in mixed powder was varied as shown in Fig. 7. Since the powder particle diameter affected the thermal conductivity, mixed powder between small and large particle was expected to have different thermal conductivity value from its original powder. Furthermore, capability of small powder particle to be in interstitial space between large powder particles can affect the overall thermal conductivity of the mixture. Fig. 7 shows the result of mixed powder on thermal conductivity when the powder was deposited under influence of gravity only. It was found that addition of large powder particle in various mixture combinations changed the value of thermal conductivity in comparison to its original powder prior to any mixing.

Table 2 Mixed powder combination of SUS 316L

Mixture	Powder Particle Diameter (µm)	
	Powder 1 (P1)	Powder 2 (P2)
A	20	50
B	10	50
C	20	100
D	10	100

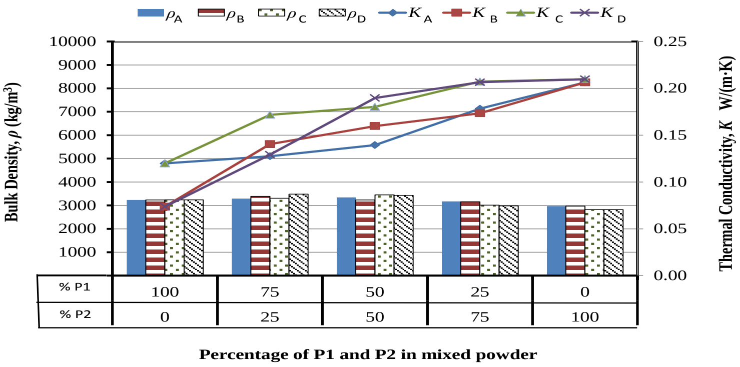

Fig. 7 Effect of mixed powder

Based on the result shown in the Fig. 7, it can be clearly seen that the values of thermal conductivity were increasing with respect to the increasing percentage of P2 for all of mixture type i.e A, B, C and D. However, reducing the existence of the air gap by mixing small powder particles in interstitial space between large powder particles did not significantly increase the thermal conductivity. This was shown in thermal conductivity of mixed powder where all of the values were below than the biggest particle diameter. This was despite slightly higher bulk density of mixed powder. In mixed powder, higher bulk density was caused by interstitial spaces between large powder particle were filled with small powder particles as shown in Fig. 9. This behaviour occurred caused by more prevalent heat conductive mechanism of large powder particles and minor influence of small powder particle. Fig. 8 shows the effect of mixed powder bulk density on thermal conductivity. Measurement for all combinations of mixed powder was repeated by compressing the surface of powder inside the cylindrical vessel. Similar behaviour as in unmixed powder, the thermal conductivity of mixed powder was increasing with respect to the bulk density.

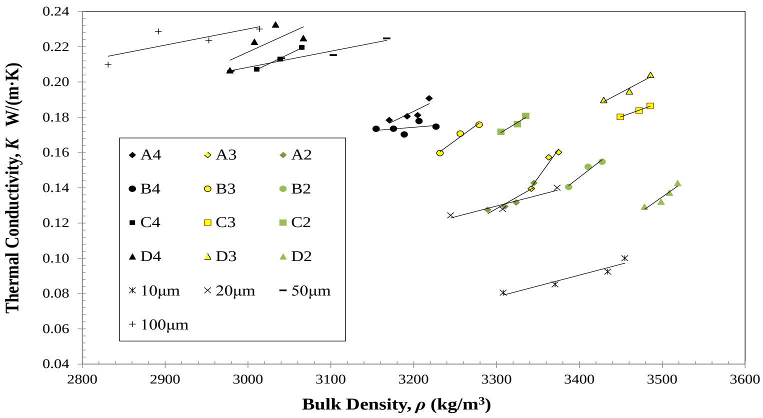

Fig. 8 Effect of mixed powder bulk density

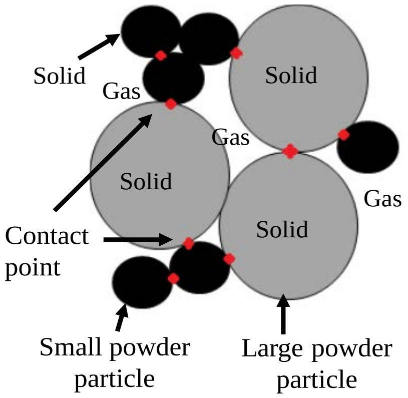

Fig. 9 Schematic view of powder particle

Effect of Porosity on Thermal Conductivity. The consolidated materials were fabricated with SCM + Cu + Ni material using LUMEX 25C SLS/SLM system. Laser processing condition used during the experiment was set at speed of 444 mm/s, 45 micron hatching size, 50 micron layer thickness and spot diameter of 0.1 mm. The laser power was varied from P=100 to 400 watt.

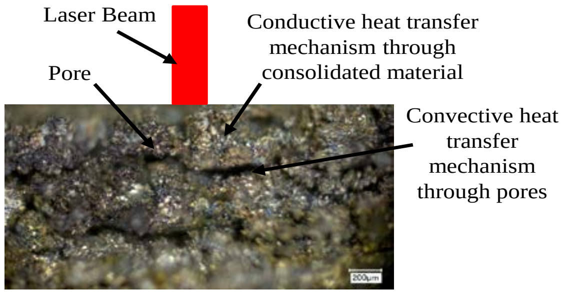

Fig. 10 Consolidated material

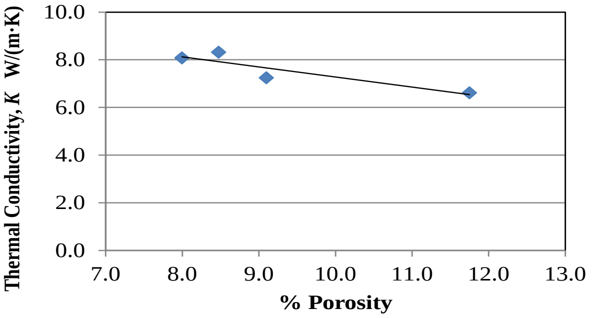

Fig. 11 Effect of porosity on thermal conductivity

Table 3 Comparison of thermal conductivity

Material	Thermal Conductivity, *K* W/(m·K)		
	Powder [6]	Consolidated	Bulk [9]
SCM + Cu + Ni	0.14	7.56	42.70

Consolidated material showed the existence of porosity as depicted in Fig. 10. The specimens were then sectioned using wire cut, and both surfaces were polished (#150 grain size). Percentage of porosity on consolidated material was analysed using image-processing software, Scion Image. The images were captured using the Keyence VHX-1000 digital microscope. The ratio of the void area to surface at area of each specimen was determined after the images were binarized and threshold at 100/255. Fig. 11 shows the effect of percentage of porosity on thermal conductivity. The result indicated that thermal conductivity was decreasing with the increase of porosity. This is due to increasing percentage of scattered pores. The pores experienced convective heat transfer mechanism, which reduced the overall heat transfer rate to measuring point. Average thermal conductivity of consolidated material was compared with a previously obtained result of metal powder and the same material in the form of bulk material. The comparison is shown in Table 3. Significant difference between the values of thermal conductivity of the same type material was due to existence of air gap and loose particle arrangement in the powder material. In consolidated material, solid structure was formed with a considerable amount of porosity. Thus, thermal conductivity of consolidated material was in between its corresponding material in powder and bulk form.

Conclusions

Based on the experiment conducted, following conclusion is obtained.

1. Air gap between metal powders particles contributed to low thermal conductivity of metal powder. However, this thermal conductivity was increasing with metal powder bulk density and powder particle diameter.
2. In a mixed metal powder with different particle diameter, the metal powder with the large particle diameter has more influence on the value of overall effective thermal conductivity.
3. Thermal conductivity of consolidated material was decreasing with the increase of porosity. This was attributed to convective type heat transfer mechanism experienced by the pores in the consolidated material.
4. High difference in thermal conductivity among powder, consolidated and solid material was attributed to distinctive heat transfer mechanism, porosity and air gap in each material type.

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