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**ORTHOGONAL ARRAY TECHNIQUE FOR OPTIMIZING THE SINTERING  
PARAMETER OF THE METAL INJECTION MOLDING (MIM) COMPACT: BEST  
FLEXURE STRENGTH**

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**ABSTRACT**

Sintering is a key step in the metal injection moulding (MIM) process, which affects the mechanical properties of the sintered part. The mechanical property of the sintered compact is resulted from tremendous sintered part densification. The paper presents an optimisation of the sintering parameter for the best flexure strength of the fine SS316L water atomised powder compact. The  $L_9$  ( $3^4$ ) orthogonal array is used in the study and four replication of the flexure strength has been recorded at each experiment trial. The analysis of variance (ANOVA) shows the sintering variables are highly significant to the flexure strength,  $\alpha = 0.005$ . The study demonstrates that the cooling rate is the most influential variable that contributes to the best flexure strength, followed by heating rate, dwell time and sintering temperature.

**KEY WORDS:** Metal Injection Moulding, orthogonal array, analysis of variance, flexure strength, sintering

**1. INTRODUCTION**

Metal injection moulding (MIM) is a net-shape process which combines the versatility of plastic injection moulding with the strength and integrity of machined, pressed or otherwise manufactured small, complex, metal parts. The process combines the design freedom of plastic injection moulding with material properties near that of wrought metals. With its inherent design

flexibility, MIM is capable of producing an almost limitless array of highly complex geometries in many different alloys ranging from stainless steels, alloy steels, and soft magnetic materials, controlled expansion materials (low CTE), and custom alloys. Design and economic limitations of traditional metalworking technologies, such as machining and casting, can be readily overcome by MIM. Competing processes include pressed powder sintering, investment casting, turning and machining [1]. The process involves combining fine metal powders with plastic binders which allow the metal to be injected into a mould using equipment similar to standard plastic injection moulding machines.

Today, MIM is serving critical performance applications in a wide range of industries and products including, automotive, aerospace and defence, cellular telephones, dental instruments, electronic heat sinks and hermetic packages, electrical connector hardware, industrial tools, fibre optic connectors, fluid spray systems, hard disk drives, pharmaceutical devices, power hand-tools, surgical instruments, and sporting equipment.

Optimisation of the processing parameter is essential to obtain high quality final parts. Rigid final part is essential to maintain an excellent performance of the powder metallurgy products especially for the tough application such as automotive, defence and industrial tools. Many earlier studies about sintering of MIM part are concerning with microstructures, densification, and sintering atmosphere (Li et al. 2003 [2]; Fu et al. 2005 [3]; Koseski et al. 2005 [4]; Suri et al. 2005 [5]; Berginc et al. 2006 [6]). Sintering parameters were optimised by adjusting the sintering variables without using any design of experiment (DOE) methodology. The traditional experimental approach that vary one variable at a time, holding all other variables as fixed does not produce satisfactory results in a wide range of experimental settings. Thus it requires a lot of experiments attempt before the optimised sintering parameter is obtained without having any statistical confidence level.

Consequently, DOE for the injection parameter has been studied by Khairur Rijal Jamaludin et al. (2008a, 2008b) [7, 8] resulting a significant optimum injection parameter for MIM feedstocks. As a consequence to the injection parameter optimisation, the sintering parameter for the final part with highest flexure strength is optimised. Beside that, the optimisation of the sintering parameter for the final part densification has been discussed by Ji et al. (2001) [9] and Jamaludin et al. (2009) [10].

## **2. EXPERIMENTAL**

MPIF 50 standard tensile bar is used as a specimen. Water atomised 316L stainless steel powder with  $D_{50}$  of 7.157  $\mu\text{m}$ , pycnometer density of 7.90  $\text{g/cm}^3$  is mixed with 73 % PEG weight of polyethylene glycol (PEG) and 25 % weight of polymethyl methacrylate (PMMA). About 2 % weight of stearic acid (SA) is used as a surfactant. As the critical powder loading of the fine water atomised powder is only 63.96 % volume, which is extremely low compared to that of the gas atomised powder, the feedstock used in this work is limited to 62.5 % volume.

Prior to the moulding, compositions are mixed in a sigma blade mixer for 95 minutes at a temperature of 70°C. Battenfeld, BA 250 CDC injection moulding machine was used to prepare

the greens while high vacuum furnace Korea VAC-TEC, VTC 500HTSF with vacuum pressure up to  $9.5 \times 10^{-6}$  mbar was used for sintering.

### 3. DESIGN OF EXPERIMENT (DOE)

There are many sintering parameters that have some effect on the properties of the sintered part. Therefore, a DOE method is necessary for the experimental work involving many inputs. The most frequently used methods are partial or full factorial design and, the Taguchi approach. With an appropriate DOE, one can quickly and with fewer amounts of trials, found whether the variables have an effect on the output quality. The Taguchi approach is mostly used in the industrial environment, but it can also be used for scientific research. The method is based on balanced orthogonal arrays (Park 1996 [11]). In this paper,  $L_9$  ( $3^4$ ) orthogonal array consisting of 9 experiment trials and 4 column is used as DOE followed by ANOVA to determine the significant level and contribution of each variables to the flexure strength. The main variables involved in this study are as shown in Table 1, while the orthogonal array used for the experiments is as shown in Table 2. The factor level for each variable shown in Table 1 refers to the maximum and minimum limit that influences the final quality of the specimens.

Table 1 Factor level (variables) in the experiment

Factor	Level		
	0	1	2
A Sintering Temperature (°C)	1340	1360	1380
B Dwell time (minute)	60	120	240
C Heating rate (°C/min)	6	8	10
D Cooling rate (°C/min)	6	8	10

### 4. RESULTS AND DISCUSSION

The flexure strength of the sintered part shown in Table 2 was measured by three point bending tests. The test is complying with the MPIF 15 standard. Four replications were made for each experiment trials. The column at the right hand side of Table 2 is the mean of the replications,  $\bar{Y}$  made for each experiments trial. As shown in Table 2, despite the factor level for all variables are at the minimum level, the mean of the flexure strength is the highest (892.74 MPa). On the other hand, the fourth trial has demonstrated that the lowest flexure strength (661.55 MPa) was obtained although the part is sintered at higher sintering temperature compared to the first trial. This is due to the formation of the liquid phase when sintering temperature was increased to 1360 °C. The increase of heating and cooling rate is believed to be another reason for the decrease of the flexure strength. However, if compact with higher powder loading is used and thus less formation of the liquid phase in the compact during sintering, stronger sintered part might be obtained with higher sintering temperature. Flexure strength which is very close to the average is obtained in the second experiment trial. This occurs at the lowest level for the

sintering temperature. But still, by increasing the dwell time, heating and cooling rate has tumbling the flexure strength.

Table 2 Orthogonal array and flexure strength

	Orthogonal array L <sub>9</sub> (3 <sup>4</sup> )				Replication (flexure strength (MPa))				$\bar{Y}$
	A	B	C	D	1	2	3	4	
Eksperiment	1	0	0	0	892.48	893.00	892.74	892.74	892.74
	2	0	1	1	735.76	736.00	735.88	735.88	735.88
	3	0	2	2	698.93	698.50	698.71	698.71	698.71
	4	1	0	1	662.09	661.00	661.55	661.55	661.55
	5	1	1	2	781.64	782.00	781.82	781.82	781.82
	6	1	2	0	704.85	706.00	705.43	705.43	705.43
	7	2	0	2	753.06	752.00	752.53	752.53	752.53
	8	2	1	0	713.98	715.00	714.49	714.49	714.49
	9	2	2	1	681.30	680.00	680.65	680.65	680.65
							Average	735.98	
							Max	892.74	
							Min	661.55	

Table 3 ANOVA for the flexure strength at  $\alpha = 0.005$

Variable	Degree of freedom, $f_n$	Sum squared, $S_n$	Variance, $v_n$	Variance ratio, $F_n$	Critical F value	Contribution, $P_n$
A	2	28514.35	14257.18	109939.56	$F_{0.005, 2, 27}=6.4885$	18.59
B	2	34041.15	17020.58	131248.63	$F_{0.005, 2, 27}=6.4885$	22.20
C	2	37948.39	18974.19	146313.30	$F_{0.005, 2, 27}=6.4885$	24.75
D	2	52836.86	26418.43	203717.11	$F_{0.005, 2, 27}=6.4885$	34.46
error	27	3.50	0.129682			0.00
Total	35	153344.26				100

Table 3 shows the analysis of variance (ANOVA) for the mean of the flexure strength shown in Table 2. The ANOVA demonstrates that all the sintering variables are highly significant at  $\alpha = 0.005$ . The cooling rate (D) has demonstrated a greatest influence to the flexure strength followed by the heating rate (C), dwell time (B) and the sintering temperature. This agrees with results shown in Table 2 that the sintered parts are becoming weaker when the cooling and heating rate as well as the dwell time and sintering temperature were increased to the next level.

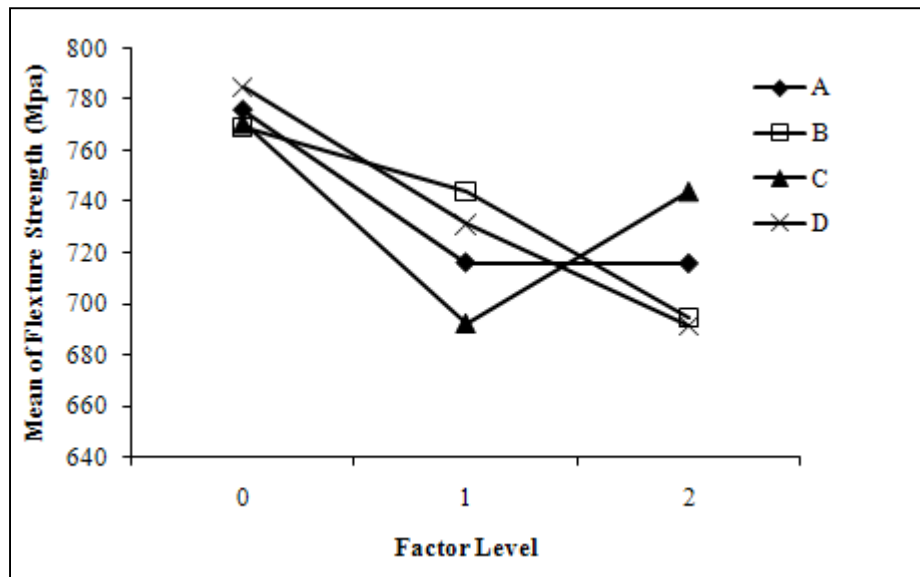


Fig. 1 Response plot for the best flexure strength

The response plot shown in Fig. 1 is referring to the average of the flexure strength at each factor level. The plot demonstrates the compact sintered at the lowest factor level is sufficient for the best flexure strength. This is by the fact that the response plot shown in Fig. 1 demonstrates sintering at the lowest factor level provides the highest mean flexure strength and it indicates the optimum parameters. The most influential factor for the best flexure strength, a cooling rate, was found to have a linear reduction of flexure strength when the cooling rate is increases to the higher factor level. However, the flexure strength was increasing when the factor level of the heating rate was increased from level 1 to level 2. As shown in Fig. 1, the increase of the heating rate results better flexure strength but it is reducing the flexure strength when the cooling rate was increased to level 2.

The optimum sintering parameter for this quality characteristic is as shown in Table 4. The optimum flexure strength is  $892.74 \pm 0.307$  MPa at 90 % confidence level. In order to verify the validity of the optimum parameter, confirmation experiment has been performed at four replications using the optimum parameter shown in Table 4 and since the result lies in between the optimum performance, thus the optimum sintering parameter is reliable.

Table 4 Optimum sintering parameter for the best flexure strength

Optimum parameter: A0 B0 C0 D0					
(Sintering temperature, 1340 °C; Dwell, 60 minit; Heating rate, 6 °C/minit; Cooling rate, 6 °C/minit)					
Optimum performance: 892.74 MPa Confidence interval: $\pm 0.307$ at confidence level of 90 % ( $\alpha = 0.1$ ) Range: 892.43 MPa $< \mu <$ 893.05 MPa					
Confirmation experiment (MPa)					
Repeat	1	2	3	4	average
(MPa)	892.48	893.00	892.74	892.74	892.74

## 5. CONCLUSIONS

The sintering parameter for the best flexure strength has been presented in the paper. An ANOVA shows the sintering variables are highly significant to the flexure strength, at a very high significant level of  $\alpha = 0.005$ . The paper demonstrates the cooling rate is the important variable for the best flexure strength, followed by the heating rate, dwell time and sintering temperature. Thus, the results shown in this paper that the diminution of the flexure strength is obvious when the cooling rate is increased. The lowest factor level is sufficient as the optimum sintering parameter for the water atomised SS316L compact at powder loading 62.5 % volume and the result has been verified by a confirmation experiment.

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