

OPTIMIZATION OF PROCESS PARAMETERS IN LASER TRANSMISSION BONDING TO INCREASE THE SHEAR STRENGTH OF AU-SN (IMCS) JOINT

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Abstract

Abstract Au-Sn solder has been currently used for soldering the laser diode silicon chip on the slider surface which is alumina (Al₂O₃) titanium carbide (TiC) in hard disk drive (HDD). However, intermetallic compounds (IMCs) form at the interface during the bonding process and result in cracks within these interfacial IMCs. As a consequence, the bonded joint failure occurs for Au-Sn (IMCs) joints with low shear stress. The shear stress is considered a major contributor to the quality and reliability of HDD. At present, the average shear strength of the Au-Sn (IMCs) joint is approximately 2.716 MPa. In this work, 4,572 Au-Sn bonded samples using the laser transmission bonding process were analysed to find suitable bonding factors to improve the shear stress of Au-Sn (IMCs). The analyse phase utilizes heat map correlation to determine 5 key process input variables (KPIVs) including (1) Temperature, (2) Stage Cross-Track (CT), (3) Stage Down-Track (DT), (4) Z-height (5) Laser power. The key process output variable (KPOV) is the shear strength of the IMCs layer between the laser diode silicon chip and the Alumina Titanium Carbide (AlTiC) substrate. Then, a response surface methodology (RSM) is performed to provide the significant factors that generate a reliable mathematical relationship between the process parameters and the desired response. The confirmation experiment performed illustrates that the new process setting of the IMCs shear strength layer is increased from 2.716 MPa to 5.050 MPa which accounts for 85.94% which is a significant improvement.

Keywords: Au-Sn bonding; Face centred central composite (FCC) design; Hard disk drive; Laser transmission bonding

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Introduction

Hard disk drive (HDD) manufacturers are striving to continually improve quality to achieve constant changes in both customers' product requirements and demands. Another requirement for hard disk drives is to be both small and inexpensive. It is very difficult to fully handle the production. HDD assembly consists of subassemblies such as spindle, head stack assembly (HSA), head gimbal assembly (HGA), media, logic board, actuator and voice coil motor as shown in Figure 1.

The HGA component is responsible for forming read and write. HGA consists of thin sheet metal attached to a slider (Song *et al.*, 2013). The HGA process is an assembly between the suspension and slider parts (Tang *et al.*, 2013). The suspension is the position that the slider slides over on the surface for a rapid spin on the media (Wang *et al.*, 2015). The slider, as shown in Figure 2, which is the most important part of the head assembly, is an electrical part, special electromagnetic, which converts magnetic into an electrical signal. It consists of suspension, reader and writer coil, air bearing surface, near field transducer (NFT), and optical waveguide (Naniwa and Nakamura, 2014). From Figure 2, a laser diode silicon chip has to be bonded on the slider surface in which the laser diode was used for read/write in HDD. However, in the assembly process for bonding the laser diode silicon chip on the slider surface which is alumina (Al_2O_3) titanium carbide (TiC) or AlTiC, it is a vital process. Au-Sn solder has been widely used for soldering electronic devices, optoelectronic devices, hermetic sealing applications and MEMS since 1990 to present (Matijasevic *et al.*, 1990; Katz *et al.*, 1993; Chromik *et al.*, 2005; Kim and Lee, 2006; Yoon *et al.*, 2007; Zhang *et al.*, 2009; Chidambaram *et al.*, 2010; Yoon *et al.*, 2011; Manikam and Cheong, 2011; Etschmaier *et al.*, 2012; Kim and Choi, 2012; Zeng *et al.*, 2012; Tollefsen *et al.*, 2013; Elmer and Mulay, 2016; Zhu *et al.*, 2016; Peng *et al.*, 2021; Lee *et al.*, 2022). This is due to it has high thermal conductivity, low melting, low elastic modulus and high strength (Chromik *et al.*, 2005; Kim and Lee, 2006; Yoon *et al.*, 2007; Chidambaram *et al.*, 2010; Manikam and Cheong, 2011; Yoon *et al.*, 2011; Zeng *et al.*, 2012).

There are many bonding methods for soldering optoelectronic devices that are commonly used currently: transient liquid phase (TLP) soldering (Li *et al.*, 2011; Chu *et al.*, 2015), isothermal diffusion (IDS) soldering (Etschmaier *et al.*, 2012), Laser soldering (Wissinger *et al.*, 2013; Deeying *et al.*, 2018) thermo-combustion (TC) soldering

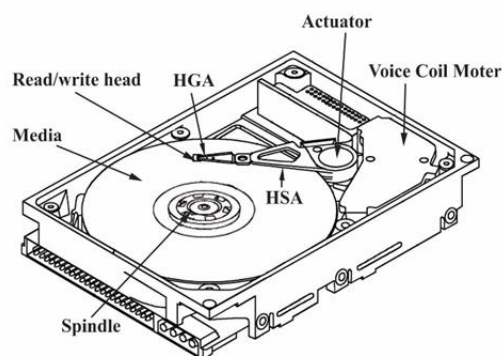


Figure 1. Hard disk drive components

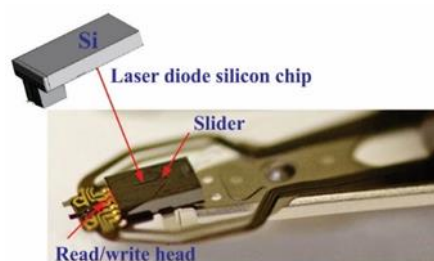


Figure 2. Head gimbal assembly

(Lee *et al.*, 2022) solid-liquid interdiffusion (SLID) soldering (Tollefsen *et al.*, 2013; Zhu *et al.*, 2016). Among those methods, the laser transmission bonding method is the most suitable one for bonding devices in HDD manufacturing.

The laser transmission bonding process is an advanced method for joining similar or dissimilar materials (Kumar *et al.*, 2017). It has many outstanding advantages, such as high precision, a small heat affected zone and non-contact point to the device (Liu *et al.*, 2012; Asséko *et al.*, 2015; Nguyen *et al.*, 2020). There are challenging great concerns due to the increasing demand for microelectronic devices, data storage, solid state chip and computer. Therefore, laser transmission bonding has a big effect on joining the electrical circuits of those devices.

However, in most soldering systems, intermetallic compounds (IMCs) form at the interface during the bonding process and result in cracks within these interfacial IMCs. As a consequence, bonded joint failure occurs for Au-Sn (IMCs) joint with low shear stress (Peng *et al.*, 2021). At present, the average shear strength of the Au-Sn (IMCs) joint is approximately 2.716 MPa. Therefore, in this work, we analyzed 4,572 Au-Sn bonded samples to

find the suitable bonding factors to improve the shear stress of Au-Sn (IMCs) using Response surface methodology (RSM). The experimental process parameters used for the analysis were x-direction movement (stage DT), y- y-direction movement (stage CT), temperature, laser power and distance between laser diode silicon chip and AlTiC substrate (Z-height).

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that is useful for problem modeling and analysis of responses of interest. RSM is influenced by the relationship between the response variables and various input parameters (independent variables). To optimize this response, a function can be expressed as

$$y = f(x_1, x_2) + \epsilon \quad (1)$$

where ϵ represents the noise or error observed in the response y . If denote the expected response by $y = f(x_1, x_2) = \eta$, then the surface represented by

$$\eta = f(x_1, x_2) \quad (2)$$

It is called a response surface. The first step in RSM is to find a suitable approximation for the true functional relationship between y and the set of independent variables. Usually, a low-order polynomial is employed in some region of the independent variables. If the response is well modeled by a linear function of the independent variables, then the approximating function is the first-order model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \epsilon \quad (3)$$

If there is curvature in the system, then a polynomial of a higher degree must be used, such as the second-order model.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \epsilon \quad (4)$$

Materials and Methods

Materials

Figure 3 shows the laser diode silicon chip to be bonded on the AlTiC. The upper part is a silicon chip and is permanently attached with a laser diode. The laser diode was used for read/write in HDD. Gold (Au) with a thickness of 850-900 nm is the substrate of the laser diode silicon chip. The lower part is AlTiC and is permanently attached with a layer of tin (Sn) substrate that has a thickness of 950-1,000 nm and an Au substrate with a thickness

of 100-200 nm. Therefore, the joint will be bonded between a laser diode silicon chip and AlTiC. Table 1 shows the chemical composition of the laser diode silicon chip that is bonded to AlTiC.

Table 1. Chemical compositions of laser diode silicon chip and AlTiC

Element	O	Si	Ti	Sn	Ta	Pt	Au
Constituents (at %)	7.2	0.1	10.9	54.5	0.2	0.1	27.0

Laser Transmission Bonding Machine

The laser transmission bonding machine used in this work is the Hamamatsu bonding machine. The fiber laser (Hamamatsu, model L 11785-61M) with a maximum output power of 10W and a wavelength of 915 ± 20 nm was used as the laser bonding source.

The laser bonding process by the bonding machine was performed using a custom computer numerical control (CNC) system.

The sequence in automatic operation can be programmed and executed as an ordered sequence. The jog tool operation of the motors for the X and Y axes allows up/down control of these coordinates. The tool preparation and inspection of the laser diode silicon chip were done before active alignment on the fixture, and coordinates for the piezo controller in the X and Y axes were given. In parallel the sliders were focused on the bonding tool head with active alignment. The laser diode silicon chip and the slider are in passive alignment when putting the fixture together. When alignment is completed, the device is ready for luminosity measurement, using a high-magnification camera. Then the laser is run continuously passing the beam through the quartz crystal, with the heating profile specified in the recipe setting. The operation causes bonding. The tool head will pick up the assembled laser diode with silicon ship and slider and move it to the outgoing tray.

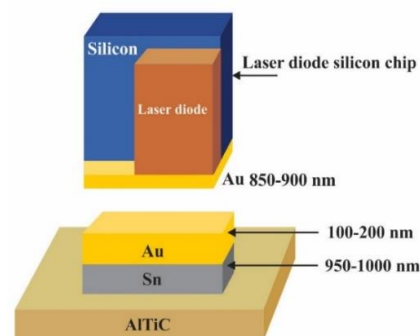


Figure 3. Laser diode silicon chip and AlTiC

The focal position is also determined by a Charge Coupled Device (CCD) vision system. This highly accurate bonding system can achieve satisfactory bonding passes through the quartz crystal surfaces. In the experiment, we first turned on the laser for a period of time to stabilize it and then bonded the Au-Sn substrate to ensure stable processing. The laser has strong coherence and high directivity. The transparency of the quartz crystal is very important because it affects the clarity of the Au-Sn bonding process. Quartz crystal is one of the most transparent materials available. It is the most favorite and technologically very critical among all hydrothermal tooling operations. The laser beam propagates along the axis of the optical system through the transparent quartz crystal with a specified purity of quartz better than 99.99%.

Experimental Method of Screening

The current average shear strength of the Au-Sn (IMCs) joint is 2.716 MPa. The data were collected daily and obtained machine parameter log files for about 1 year. Therefore, there are 4,572 data points. In the analysis, tools such as big data technique from Python software 3.7 and heat map correlation were applied to find out the key process input variables (KPIVs) as shown in Figure 3. The 5 KPIVs with high correlation are in the following lists: 1) temperature 2) stage CT, 3) stage DT, 4) Z-height and 5) laser power.

The heat map is a common method of visualizing complex relationships among large groups of factors. A represents the strength and direction of relationships between numerical variables, which are related to each other. The heat map plot has rows and columns for each variable, and the correlation between them as indicated in the cells. The values in the cells determined the strength of the relationship with positive values representing a positive relationship and negative values representing a negative relationship. The range of correlation values is between -1 and 1. The color of the cells makes it easy to identify at a glance.

Figure 4 shows the heat map focused on relationships between shear strength and input features in a model. Heat map results are listed for the top 5 interesting factors and can be concluded as follows:

- 1) Stage DT has the most correlation with shear strength at 0.42 (42%),
- 2) Temperature correlates with shear strength at 0.37 (37%),
- 3) Stage CT correlates with shear strength at 0.34 (34%),
- 4) Laser power correlates with shear strength at 0.28 (28%), and

5) Z-height has the least correlation with shear strength at 0.16 (16%), respectively.

Other parameters are not significant factors in critical variable parameter

The process parameters comprised of 1) Temperature is the silicon surface temperature, 2) Stage CT is a direction attachment in y-axis, 3) Stage DT is a common direction attachment in x-axis, 4) Z-height is the distance between laser diode silicon chip and AlTiC substrate, 5) Laser power is a common factor resulting in heat transmission to melting Au pad 800 nm combine Sn 1,000 nm pad to Au-Sn IMCs layer joint (Rodríguez-Vidal *et al.*, 2014). The force of pressing the laser diode silicon chip attached to AlTiC is kept constant throughout the experimentation.

Design of Experiment

Experiments were designed using the Box-Behnken design (BBD) of response surface methodology (RSM) approach, analysis of variance (ANOVA) and design of experiment (DOE) parameters. BBD can investigate the process with a relatively small number of runs as compared with the Face Central Composite Design (FCCD).

After performing these analyses, the top 5 KPIVs are performed to identify the characteristic factors in the improvement phase. The 5 KPIVs shown in Table 2 are established by the Face Centered Central Composite (FCC) design as



Figure 4. Heat map correlation technique for shear strength of Au-Sn (IMCs) joint

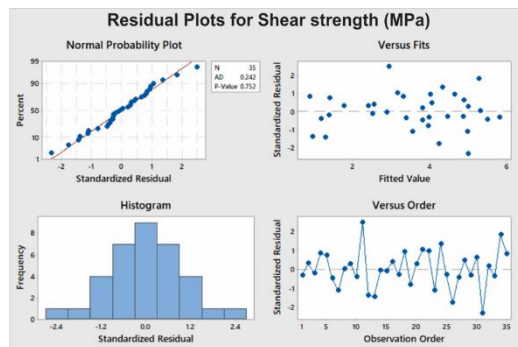
Table 2. Process parameter of 5 KPIVs and level of the factor in design of experiment

No.	Factor	Unit	Level of the factor in DOE	
			Low (-)	High(+)
1	Temperature	°C	270.5	316.9
2	Stage CT	degree	-0.0908	0.0417
3	Stage DT	degree	-0.015	0.005
4	Z-Height	μm	-0.1	1.0
5	Laser Power	Watt	3.8	4.1

Table 3. ANOVA for the shear strength of Au-Sn (IMCs) joint in quadratic model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	10	70.3694	7.03694	45.13	0.0000
Linear	5	24.5963	4.91926	31.55	0.0000
Temperature	1	0.0086	0.00862	0.06	0.8160
Stage CT	1	2.3432	2.34317	15.03	0.0010
Stage DT	1	0.2214	0.22141	1.42	0.2450
Z-Height	1	2.7417	2.74172	17.58	0.0000
Laser Power	1	7.3517	7.35169	47.15	0.0000
Square	3	6.1971	2.06571	13.25	0.0000
Temperature*Temperature	1	0.7482	0.74819	4.80	0.0380
Stage CT*Stage CT	1	2.9105	2.91053	18.67	0.0000
Stage DT*Stage DT	1	1.843	1.84297	11.82	0.0020
2-Way Interaction	2	8.7989	4.39944	28.22	0.0000
Temperature*Z-Height	1	7.1404	7.14037	45.79	0.0000
Z-Height*Laser Power	1	0.7699	0.76988	4.94	0.0360
Error	24	3.7421	0.15592		
Total	34	74.1115			

a method also studies the second-order terms of the variables on the response surface, main effects model and interaction effects model. The FCC is an effective tool for collecting information on the positive and negative responses of the process input parameters.

**Figure 5. Residual plots for the shear strength of Au-Sn (IMCs) joint**

For modeling, analysis, and optimization, in general, the relationship between the response variables and input parameters of the FCC design relationship can be expressed by Equation 5.

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \epsilon \quad (5)$$

Result and Statistical Analysis

KPIVs selected in the previous section are considered factors or process parameters that potentially affect the shear stress of the Au-Sn (IMCs) joint. In the improvement phase, the objective is to search for a better or optimum process

parameters which are able to increase the shear stress of the Au-Sn (IMCs) joint to achieve the target of this study. The sample size required for each run is determined to achieve the acceptable power of the test. According to the hypothesis test, the samples for each run should be at least 8 to obtain a power test of 0.95.

The analysis of variance requires three principle assumptions including normality, variance stability, and independence. These assumptions can be checked by using the residual plots. The plots of residual for undercut defects are shown in Figure 5. It indicated that there is no strong evidence of violating these three assumptions for ANOVA. The fitted empirical models will be enhanced by eliminating terms backward and keeping only those that contribute to their significance.

Analysis of Variance

Table 3 shows the results of the analysis of variance (ANOVA) for the shear strength of the Au-Sn (IMCs) joint. The statistical technique to study a response variety by p-value indicates that the terms with a p-value is less than 0.05 are significant. It also presents other adequacy measures $R^2 = 94.95\%$, adjusted $R^2 = 92.85\%$ and predicted $R^2 = 89.00\%$. It is known as the coefficient of determination and is close to 100%. The fitted second-order model to the shear strength is shown in Equation (5) and the estimated effects and coefficients, t-statistic and p-value of each term are given in Table 4.

$$\begin{aligned} \text{Shear strength (MPa)} = & -82.6 + 0.561 \text{ Temperature} \\ & - 10.89 \text{ Stage CT} + 1213 \text{ Stage DT} \\ & - 100.6 \text{ Z - Height} + 6.07 \text{ Laser Power} \\ & - 0.001128 \text{ Temperature} * \text{Temperature} \\ & + 222.0 \text{ Stage CT} * \text{Stage CT} \\ & + 80221 \text{ Stage DT} * \text{Stage DT} \\ & + 0.2292 \text{ Temperature} * \text{Z - Height} \\ & + 7.70 \text{ Z - Height} * \text{Laser Power} \end{aligned} \quad (5)$$

Table 4. Estimated effects and coefficients for the shear strength of Au-Sn (IMCs) joint

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.585	0.229	15.68	0.0000	
Temperature	0.049	0.21	0.24	0.8160	2.27
Stage CT	-1.445	0.373	-3.88	0.0010	11.89
Stage DT	-0.34	0.285	-1.19	0.2450	10.96
Z-Height	-1.561	0.372	-4.19	0.0000	8.47
Laser Power	1.431	0.208	6.87	0.0000	6.02
Temperature*Temperature	-0.607	0.277	-2.19	0.0380	1.52
Stage CT*Stage CT	0.976	0.226	4.32	0.0000	2.10
Stage DT*Stage DT	0.846	0.246	3.44	0.0020	2.31
Temperature*Z-Height	2.925	0.432	6.77	0.0000	2.40
Z-Height*Laser Power	0.636	0.286	2.22	0.0360	4.04

To assess the quality of laser bonding, the shear strength was determined. It is seen that the shear stress increases with the suitable melting temperature of Au and Sn substrates. The shear stress is enhanced and the bonding quality is determined by the melt. The appropriate stage CT, Z-height, and laser power are crucial during laser transmission bonding.

The main effects plot for shear strength is shown in Figure 6. Among all the parameters, the temperature and stage DT are the least significant. The decrease in the stage CT and Z-height are high shear strength. The behavior of the laser power increases and thus results in high shear strength.

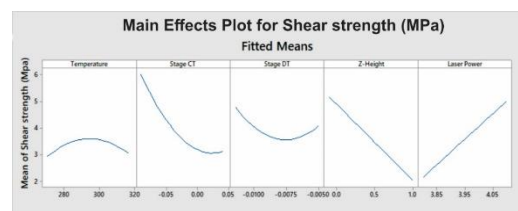
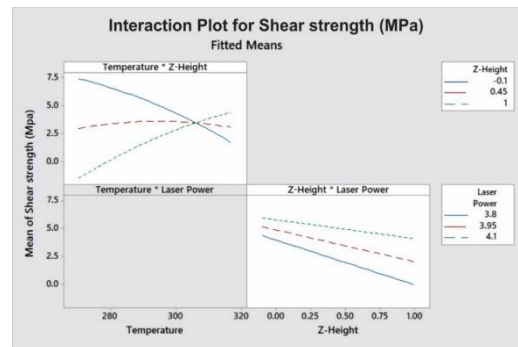
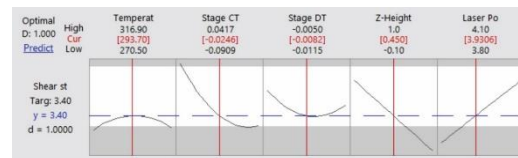
Interaction Response Surface Analysis for Shear Strength

The analysis steps in the method are interaction plots of two pairs with significant effects on shear strength as shown in Figure 7. It represents the interaction effect of temperature and Z-height. At a temperature lower than 305°C and Z-height is less than -0.1 μm which is the melting point of a combination of Au and Sn bonding. It increases shear strength. Figure 7 also depicts the interaction effect of Z-height and laser power for shear strength. The laser power was in the range of 3.80 to 4.1 W and Z-height is less than 0.5 μm can achieve shear strength.

Optimal Process Parameters

The response variable prediction, $\hat{y}$, or shear strength is contributed by the experiment as a quadratic mathematical model in the un-coded factors variables and can be expressed by:

The linear and second-order polynomials were fitted to explain the optimal process parameters by Minitab V.17 statistical program on the response optimizer as shown in Figure 8. The optimal process parameters which yield the shear strength are given in Table 5.

**Figure 6. Main effects plot for shear strength****Figure 7. Interaction plot for shear strength****Figure 8. Response Optimizer report**

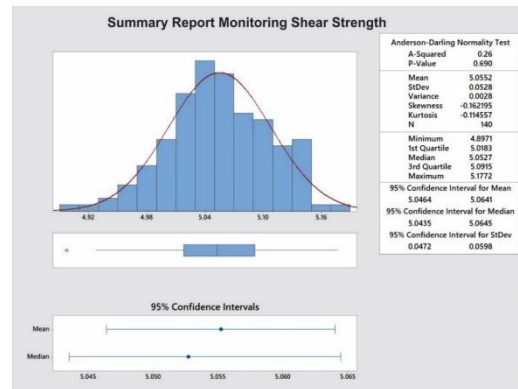
Results and Validation

The result was found that the predicted values are in high confidence with the experimental values. Then, the second-order mathematical models have a good

Table 5. Predicted value and optimal process parameters for the shear strength of Au-Sn (IMCs) joint

Process Parameters	Predicted Value	Optimal Process parameters
Shear strength of Au-Sn (IMCs) joint (MPa)	3.4	-
Temperature (°C)	-	293.70
Stage CT (Degree)	-	-0.0246
Stage DT (Degree)	-	-0.0082
Z-height (um)	-	0.450
Laser Power (Watt)	-	3.9

agreement to predict the response variable accurately. The Au Sn phase diagram reveals that an eutectic is situated at 278°C. It is essential agreement with the experimental reported temperature of 293.70°C. The confirmation experiment using the optimum process parameters was performed by producing 140 samples. It was found that the shear strength of the Au-Sn (IMCs) joint increased from 2.716 to 5.050 MPa which is acceptable. The hypothesis testing displayed in Figure 9 indicates that the shear strength of the Au-Sn (IMCs) joint significantly increased by the new process. Increasing laser power leads to an increase in shear strength (Khan *et al.*, 2011; Wang *et al.*, 2012; Kumar *et al.*, 2017; Chatterjee *et al.*, 2019).

**Figure 9. Validation of test results**

Conclusions

In this work, it can be concluded as follows:

- 1) The second-order mathematical models for the shear strength of Au-Sn (IMCs) joint have been developed by the second-order models. According to the mathematical models, the z-height and laser energy have a maximum consequence on the shear strength of the Au-Sn (IMCs) joint.
- 2) The optimal process parameters including the temperature 293.70°C, Stage CT = -0.0246 degrees, Stage DT = - 0.0082 degrees, Z- height = 0.450 µm and laser power = 3.9 watts with the shear strength of Au-Sn (IMCs) joint of 3.4 MPa.
- 3) There is a good achievement between the predicted values and process parameters values. The confirmation of the second-order mathematical models in various predictive shear strengths of Au-Sn (IMCs) joint was carried out with the validation experiment. The result revealed the average shear strength of the Au-Sn (IMCs) joint between the experimental values and the predicted value which is reflected in the optimal process conditions with less error.
- 4) It can be observed that RSM by using FCC can achieve adequately mathematical models which describe the relationship between the optimum process parameters to achieve the average shear strength of the Au-Sn (IMCs) joint.

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Disclosures

The authors declare no conflicts of interest.

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