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Evaluation of microstructure and mechanical properties of squeeze overcast Al7075-Cu composite joints

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Abstract: Al7075-Cu composite joints were prepared by the squeeze overcast process. The effects of melt temperature, die temperature, and squeeze pressure on hardness and ultimate tensile strength (UTS) of squeeze overcast Al7075-Cu composite joints were studied. The experimental results depict that squeeze pressure is the most significant process parameter affecting the hardness and UTS. The optimal values of UTS (48 MPa) and hardness (76 HRB) are achieved at a melt temperature of 800 °C, a die temperature of 250 °C, and a squeeze pressure of 90 MPa. Scanning electron microscopy (SEM) shows that fractured surfaces show flat-faced morphology at the optimal experimental condition. Energy-dispersive spectroscopy (EDS) analysis depicts that the atomic weight percentage of Zn decreases with an increase in melt temperature and squeeze pressure. The optimal mechanical properties of the Al7075-Cu overcast joint were achieved at the Al_2Cu eutectic phase due to the large number of copper atoms that dispersed into the aluminum melt during the solidification process and the formation of strong intermetallic bonds. Gray relational analysis integrated with the Taguchi method was used to develop an optimal set of control variables for multi-response parametric optimization. Confirmatory tests were performed to validate the effectiveness of the employed technique. The manufacturing of squeeze overcast Al7075-Cu composite joints at optimal process parameters delivers a great indication to acknowledge a new method for foundry practitioners to manufacture materials with superior mechanical properties.

Keywords: squeeze overcast joints; Al7075-Cu composite joints; mechanical properties; gray relational analysis; Taguchi method

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1 Introduction

Squeeze casting is a combination of forging and casting processes to produce parts with better mechanical properties [1]. It improves the quality of the products regarding mechanical properties, dimensional accuracy, and surface finish. Due to low porosity and improved mechanical properties, squeeze casting is considered superior in the classification of permanent mold casting [2]. Squeeze cast products are attractive for essential applications in the aerospace industry due to their superior mechanical characterizations [3]. However, it is challenging to manufacture these parts using the squeeze casting method to enhance the strength-to-weight ratio at a low cost. Solid-liquid bonding methods have emerged as an attractive option to cope with this limitation.

Solid-liquid bonding methods such as hot dipping [4] and overcasting [5-8] have gained significant impact in modern firms due to their high production efficiency and low manufacturing cost. Solid-liquid bonding, also known as squeeze overcasting, is a manufacturing process in which two dissimilar or similar materials, one in liquid while the other in solid form are brought into interact with each other. In this manner, a diffusion-reaction zone is formed between the two materials, and a continuous metallic transition occurs from one metal to the other, resulting in the formation of squeeze overcast joints [9]. Papis et al. [10] fabricated the squeeze overcast joint of liquid and solid magnesium (Mg) alloy, in which pure Mg (AJ62) melt was poured into a solid Mg (AZ31) substrate by replacing the oxide film on the solid AZ31 substrate with electro-deposited Zn coating Zn/$MgZn_2$. Results showed that the electro-deposited Zn coating Zn/

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$MgZn_2$ has a noteworthy positive effect on obtaining the well-defined and defect-free continuous metallurgic AZ31-AJ62 squeeze overcast joint. Hajjari et al. [11] proposed a promising approach to joining lightweight couples of Al-Mg by a squeeze overcasting technique, and it was found that shear strength increases with decreasing the interface thickness.

Squeeze overcasting has attained abundant consideration in the squeeze overcast joint method due to its high efficiency, good performance, and low fabrication cost. The squeeze overcasting method has been successfully used to manufacture the Al-Al [5, 6, 12], Mg-Al [13,14], Al-Cu [15] and Mg-Mg alloy [10]. However, the application of the squeeze overcasting technique in the Al-Cu joint is still minimal because copper inserts are usually shielded by an oxide layer, that is not easily settable by metallic melts. This oxide layer does not liquefy during the casting process and prevents the development of metallic joints. Liu et al. [15] achieved sound metallic bonding of the Al-Cu by eliminating the oxide layer with a Zn coating, which was deposited onto the copper inserts using the thermal spraying method. It was also revealed that the Al-Cu eutectic layer thickness decreases with the rise of pouring temperature and squeeze pressure, and the optimal ultimate tensile strength (UTS), electrical resistance, and micro hardness were achieved at 700 °C pouring temperature and 90 MPa squeeze pressure. Additionally, Liu et al. [8] observed that all the pouring temperature, applied pressure, and surface treatment have significant effects on the microstructure and mechanical properties of the Al-Al squeeze overcast joint. The tensile strength of the Al-Al squeeze overcast joint was enhanced by 10% when squeeze pressure was applied during the solidification stage as compared to the gravity casting. Ali et al. [6] reported that aging treatment increased micro-hardness and UTS of squeeze overcast Al2024-Al2024 joints by 12.4% and 9.8%, respectively. Additionally, it was found that the most prominent process parameters influencing the UTS and micro-hardness are squeeze pressure and melt temperature. In another article, Ali et al. [5] observed that the pre-heating temperature of the solid AA2026 insert also has a significant effect on the improvement of the micro hardness and ultimate tensile strength of AA2026-2026 squeeze overcast joints.

It can be concluded that melt temperature, die temperature, and squeeze pressure significantly affect the mechanical properties of overcast squeeze joints. Additionally, aluminum is the most commonly used liquid material in squeeze overcast joints due to its unique mechanical properties such as low density, high formability, and high strength [16]. But the application of Al7075 as liquid metal is a challenging task in the squeeze overcast joints due to its high hot tearing tendency. Therefore, this research aims to optimize the squeeze overcast process parameters using the Taguchi method to achieve the best mechanical properties of squeeze overcast Al7075-Cu composite joints. Scanning electron microscope (SEM) micrographs were employed to explain the effect of process parameters on the joint interface. Further, grey relational analysis (GRA) was performed to develop an optimal configuration of controlled input process variables for multi-response parametric optimization.

2 Experimental

2.1 Material and process parameters selection

The chemical compositions of selected commercial Al7075 and copper insert materials obtained by the spectrometry technique are listed in Table 1. The process parameters with the designed three levels are tabulated in Table 2. The selection of these process parameters was based on literature. The limitations of the selected parameters were identified through trial runs to achieve the defect-free overcast joints [17]. Nine experiments were designed according to the Taguchi orthogonal (L9) array, as indicated in Table 3.

Table 1: Chemical compositions of Al7075 and Cu (wt.%)

Elements	Si	Fe	Cu	Mg	Mn	Zn	Cr	Ni	Ti	Al
Al7075	0.4	0.5	1.2	2.1	0.3	5.1	0.18	–	0.2	Bal.
Cu	–	1.5	Bal.	–	0.7	–	–	10	–	–

Table 2: Levels of process parameters

Process parameter	Unit	Levels		
		Low	Medium	High
Squeeze pressure	MPa	60	90	120
Melt temperature	°C	750	800	850
Die temperature	°C	150	200	250

Table 3: L9 Taguchi orthogonal array experiment design

Specimen No.	Squeeze pressure (MPa)	Melt temp. (°C)	Die temp. (°C)	UTS (MPa)	Hardness (HRB)
1	60	750	150	18	55
2	60	800	200	30	65
3	60	850	250	25	61
4	90	750	200	38	68
5	90	800	250	48	76
6	90	850	150	32	69
7	120	750	250	30	71
8	120	800	150	32	80
9	120	850	200	29	72

2.2 Experimental procedure

Firstly, cubic copper solid inserts of 4 mm×13 mm×90 mm were machined using a manual vertical milling machine, and Al7075 rods were cut into the desired number of pieces using the manual lathe machine for melting according to the cavity capacity of the crucible. The crucible can hold 5 kg of Al7075 to perform pouring process, but each squeeze cast billet needs 2 kg of Al7075. Therefore, 2.5 kg of Al7075 was used for each pouring process to ensure the correct filling of die cavity.

The lubricants and oxide layers on the copper inserts were removed with abrasive papers before being polished to a smooth and burs-free surface. The process of polishing was carried out in three stages, including: (i) degreasing at ambient temperature for 5 min using C_3H_6O; (ii) alkali etching at 55 °C for 1 min using NaOH solution (100 g·L^{-1}, pH>13); and (iii) acid pickling process at room temperature for 30 s in 50% HNO. Water rinsing of copper inserts was completed before each stage of surface cleaning. Furthermore, 5 mm thick Zn layer was used for successful bonding between Al7075 and Cu during the overcasting process. Zinc coating enhanced the wettability between molten aluminum alloys and solid copper inserts and protects the copper inserts from oxidation [15].

After degreasing and polishing, the Al7075-Cu squeeze overcast joint was fabricated using a vertical hydraulic press (with a capacity of 100 t) with a H13 forged steel die. The overcast joint manufacturing process consists of six stages as described: (i) an electric furnace with a heating capability of 1,200 °C was used to melt the Al7075 for squeeze overcasting; (ii) the copper inserts were injected into the ejection pin and insured that solid insert seated correctly in its position and die block arrangement properly clamped at the platform of press; (iii) the die temperature was achieved with the help of oxyacetylene torch and measured with the help of infrared thermometer (SMARTSENSOR: AR330); (iv) when required temperature of die and melt achieved, the crucible was taken out from the furnace, while slag was removed from the top of the melt, and then the melt was poured into the die cavity; (v) after pouring process, the pressure was applied on the molten Al7075 and holding for 1 min [18] for all the billets manufacturing; and (vi) the last stage includes the unclamping of the die from the base of press, and the solidified billets were taken out.

2.3 Output parameters measurement

For UTS and hardness testing, the samples of squeeze overcast Al7075-Cu joint were obtained from the center of cylindrical cast billet and machined (through milling machine) into a rectangular shape according to ASTM: E8/E8M-11 standard [19]. The tensile test was performed on a PC controlled universal tensile tester (with the capacity of 70 kN) at a strain rate of 0.005 mm·s^{-1} at ambient temperature. Three samples were examined in each experimental condition to assure repeatability. The INSIZE ISH-RD200 manual digital Rockwell hardness tester with a 1.5875 mm diameter steel ball with scale "B" and a 980 kg·f load was used for hardness testing. The hardness of squeeze overcast Al7075-Cu joint was measured at the interface region from all the four sides of the sample to ensure repeatability and reduce the error. For each measurement, the load was applied for 10 s, and the average of three measurements was recorded.

3 Results and discussion

3.1 Ultimate tensile strength (UTS)

The signal-to-noise (S/N) ratio and means for each of the nine experiments were achieved through Minitab Software 19.0, and the results are presented in Table 4. Responses for S/N ratios and means are depicted in Tables 5 and 6, respectively. Delta values and ranks show that squeeze pressure has prominent influence on UTS followed by melt temperature and die temperature. Sample 5 gives the highest S/N ratio, and the optimal process variables are 90 MPa squeeze pressure, 250 °C die temperature and 800 °C melt temperature.

Table 4: S/N ratio of UTS

Sample No.	Squeeze pressure (MPa)	Melt temperature (°C)	Die temperature (°C)	S/N ratio
1	60	750	150	25.105
2	60	800	200	29.542
3	60	850	250	27.958
4	90	750	200	31.595
5	90	800	250	33.624
6	90	850	150	30.103
7	120	750	250	29.542
8	120	800	150	30.103
9	120	850	200	29.248

Table 5: Response table for S/N ratios

Level	Squeeze pressure	Melt temperature	Die temperature
1	27.54	28.75	28.44
2	31.77	31.09	30.13
3	29.63	29.10	30.38
Delta	4.24	2.34	1.94
Rank	1	2	3

Table 6: Response table for means

Level	Squeeze pressure	Melt temperature	Die temperature
1	24.33	28.67	27.33
2	39.33	36.67	32.33
3	30.33	28.67	34.33
Delta	15.00	8.00	7.00
Rank	1	2	3

The main effect plots for means and S/N ratios are shown in Figs. 1 and 2, respectively. It can be found that UTS increases with an increase in squeeze pressure and melt temperature up to the middle level, whereas a further increase in these two process parameters yields a decrease of UTS. This is because the intermetallic bonding between Al7075 and copper is weaker at a higher level of these two process parameters due to the complete removal of the Zn coating layer from the surface of solid copper. Additionally, premature solidification and incomplete melting of the Zn coating are the causes of weak intermetallic bonding at lower level of these two process parameters. Complete melting of Zn coating and mature solidification occur at the middle level of these two process parameters, so that stronger intermetallic bonding is achieved, which yields a higher UTS value [15]. Furthermore, it is also observed that UTS increases with a rise in die temperature because casting defects such as cold shut are reduced, and the fluidity of molten metal increases at a higher die temperature [6].

The ANOVA table was generated at 95% confidence intervals to achieve accurate results and evaluate the practical significance of the results. It can be seen from Table 7 that all process parameters significantly affect the UTS (P value less than 0.05). It is also observed that the squeeze pressure contribution towards UTS is higher than any other process parameter. The R^2 and adjusted R^2 values are extremely near to 1, indicating that the model is adequate [21].

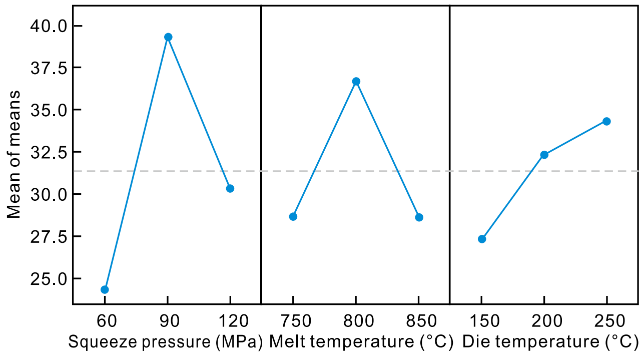


Fig. 1: Main effect plot for means

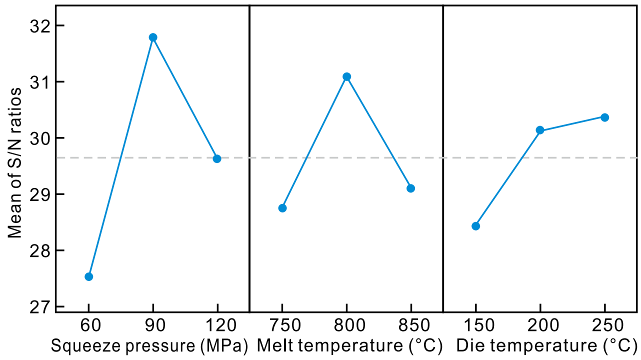


Fig. 2: Main effect plot for S/N ratios

Table 7: ANOVA table for UTS

Source	df	Seq. SS	Adj. SS	Adj. MS	*F*	*P*	Percentage contribution
Squeeze pressure	2	342.000	342.000	171.000	171.00	0.006	62.408
Melt temperature	2	128.000	128.000	64.000	64.00	0.015	23.358
Die temperature	2	78.000	78.000	39.000	39.00	0.025	14.233
Residual error	2	2.000	2.000	1.000			
Total	8	550.000					
Model summary							
S=1.0000			R^2=99.64%				R^2 (adj.)=98.55%

3.2 Hardness

It can be observed from Table 8 that Specimen 5 gives the highest S/N ratio, and the optimal combination of process parameters are 90 MPa squeeze pressure, 250 °C die temperature, and 800 °C melt temperature. Response tables for S/N ratios and means are shown in Tables 9 and 10, respectively.

Figures 3 and 4 depict main effect plots for means and S/N ratios, respectively. It is observed that when the melt temperature increases, the hardness of the Al7075-Cu overcast joint interface increases, but the hardness begins to decrease with further increase of the melt temperature. The hardness increases with an increase in squeeze pressure and die temperature. Squeeze pressure has a more significant effect on hardness as compared to die temperature and melt temperature.

Table 8: S/N ratio of hardness

Specimen No.	Squeeze pressure (MPa)	Melt temperature (°C)	Die temperature (°C)	S/N ratio
1	60	750	150	34.807
2	60	800	200	36.258
3	60	850	250	35.706
4	90	750	200	36.650
5	90	800	250	37.616
6	90	850	150	36.777
7	120	750	250	37.025
8	120	800	150	38.061
9	120	850	200	37.146

Table 9: Response table for S/N Ratios

Level	Squeeze pressure	Melt temperature	Die temperature
1	35.59	36.16	36.55
2	37.01	37.31	36.69
3	37.41	36.54	36.78
Delta	1.82	1.15	0.23
Rank	1	2	3

Table 10: Response table for means

Level	Squeeze pressure	Melt temperature	Die temperature
1	60.33	64.67	68.00
2	71.00	73.67	68.33
3	74.33	67.33	69.33
Delta	14.00	9.00	1.33
Rank	1	2	3

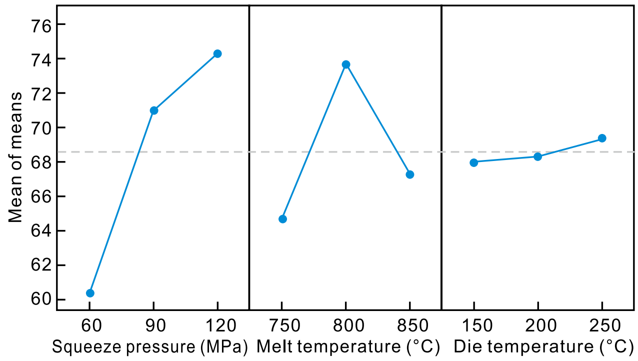


Fig. 3: Main effect plot for mean of hardness

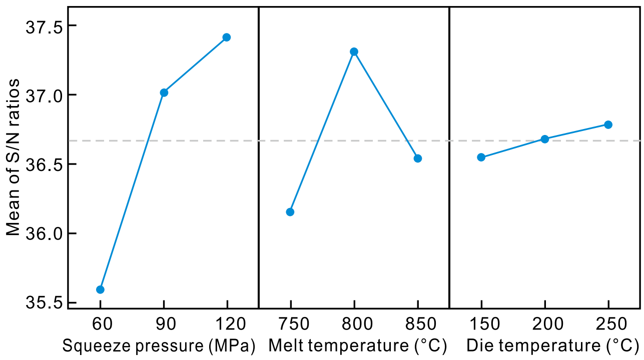


Fig. 4: Main effect plot for S/N ratio of hardness

From ANOVA Table 11, it can be found that since their *P*-value is less than 0.05, the squeeze pressure and melt temperature have significant effect on hardness. The squeeze pressure contribution is higher than the melt and die temperature.

3.3 Scanning electron microscopic analysis

3.3.1 Interface microstructure and fractography

The interface microstructure and fractography of the flat surface of squeeze overcast Al7075-Cu joints under two experimental conditions were observed with an Inspect S50 scanning electron microscope. When process parameters are at a low level (60 MPa squeeze pressure, 750 °C melt temperature, and 150 °C die temperature), Zn coating cannot be melted completely, resulting in insufficient wettability between the Al7075 squeeze cast material and solid copper insert, as shown in Fig. 5(a). It is also observed that brittle fracture shows cluster-like morphology and interdendritic porosity forms at the low level of process parameters. Weak intermetallic bonding is observed between the solid copper inserts and Al7075 material, as shown in Fig. 6(a). These inherent defects are causes of low hardness and ultimate tensile strength. Strong metallic bonding is achieved at the medium level of process parameters (800 °C melt temperature, 90 MPa squeeze pressure, and 250 °C die temperature) due to the adequate melting of the Zn layer, as depicted in Fig. 6(b). The adequate melting of the Zn-coated layer makes it easier for the copper insert to diffuse into the Al7075 melt. Furthermore, brittle fracture with flatter face morphology is observed due to the rise in melt temperature and squeeze pressure, as depicted in Fig. 7(a). The flatter morphology is attributed to the reduction of the shrinkage cavities, macro cracks, and the formation of thick

Table 11: ANOVA table of hardness

Source	*df*	Seq. SS	Adj. SS	Adj. MS	*F*	*P*	Percentage contribution
Squeeze pressure	2	320.889	320.889	160.444	51.57	0.019	70.99
Melt temperature	2	128.222	128.222	64.111	20.61	0.046	28.37
Die temperature	2	2.889	2.889	1.444	0.46	0.683	0.633
Residual error	2	6.222	6.222	3.111			
Total	8	458.222					
Model summary							
S=1.638			R^2=98.64%				R^2 (adj.)=94.57%

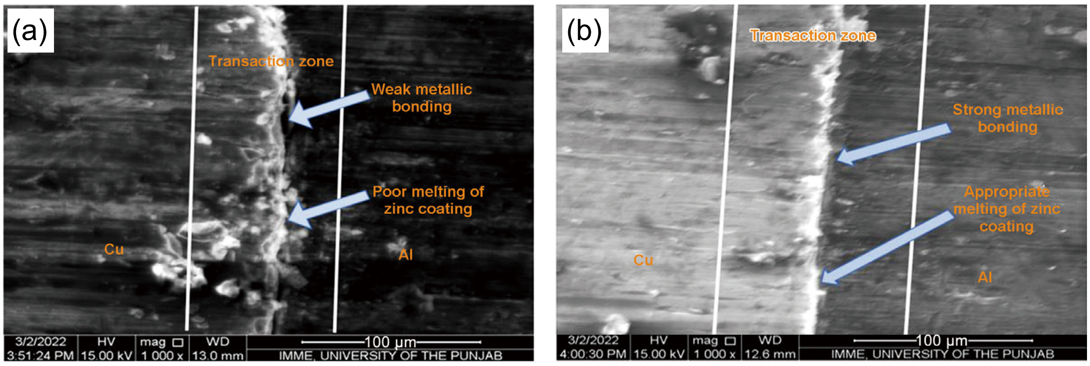


Fig. 5: Interfacial microstructure analysis of specimens manufactured at 60 MPa squeeze pressure, 750 °C melt temperature, and 150 °C die temperature (a); and 90 MPa squeeze pressure, 800 °C melt temperature and 250 °C die temperature (b)

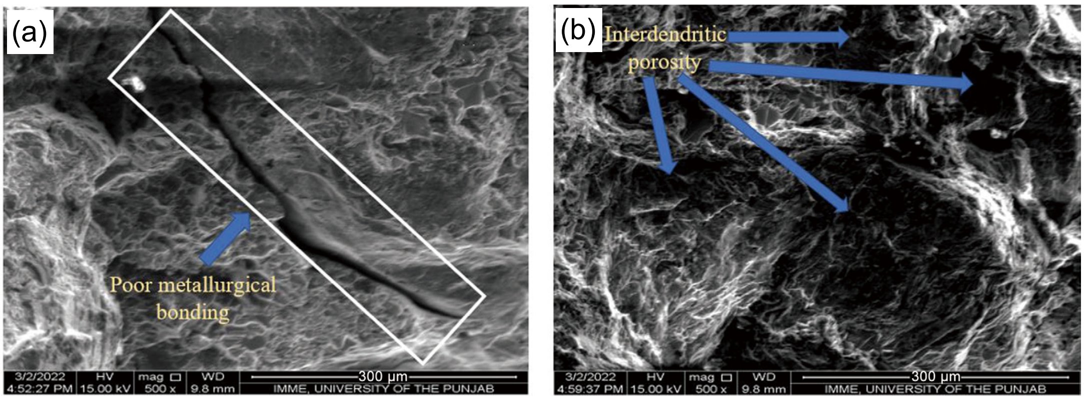


Fig. 6: SEM images of fracture surface of specimens manufactured at 60 MPa squeeze pressure, 750 °C melt temperature, and 150 °C die temperature showing poor bonding (a) and interdentritic porosity (b)

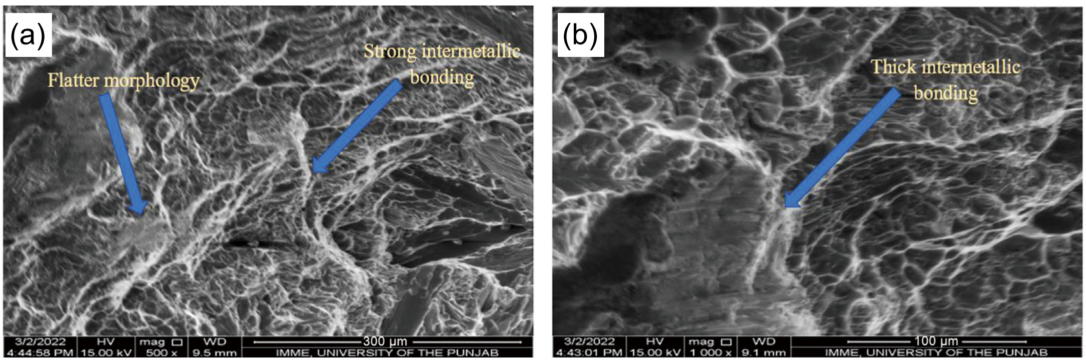


Fig. 7: Fracture surface SEM images of specimens manufactured 90 MPa squeeze pressure, 800 °C melt temperature, and 250 °C die temperature showing brittle fracture (a) and thick intermetallic bonding between Al7075 and Cu inserts (b)

intermetallic bonding layer between Al7075 and Cu inserts, as evident from Fig. 7(b). As a result, the optimal values of ultimate tensile strength of 48 MPa and hardness of 76 HRB are achieved. It can be concluded that rise in squeeze pressure and melt temperature reduce the macro cracks. The increment of squeeze pressure up to the optimal level is a reason for reducing the inherent defects like shrinkage cavities and macro cracks, which are depicted by their flatter morphology in the cast parts [7, 22–24].

3.3.2 Interface topography analysis

Topography analysis of the interfaces was performed using a scan electron microscope (SEM) to examine the influence of input parameters on hardness and UTS. Images of the flat surface of the specimen under two experimental conditions are schematically presented in Fig. 8. The thickness of the Al7075-Cu eutectic layer increases as the melt temperature rises from 750 to 800 °C. This is because that diffusion time increases as the thickness of the bonding layer increases [15]. Consequently, many Cu atoms diffuse into the A17075 casting material, resulting in a higher UTS value. Furthermore, the contact area between the Cu insert and Al7075 increases with the rise of squeeze pressure from 60 to 90 MPa, as shown in Fig. 8. The increment of contact area leads to a more compact microstructure and an improved cooling rate during solidification. Furthermore, it is important to

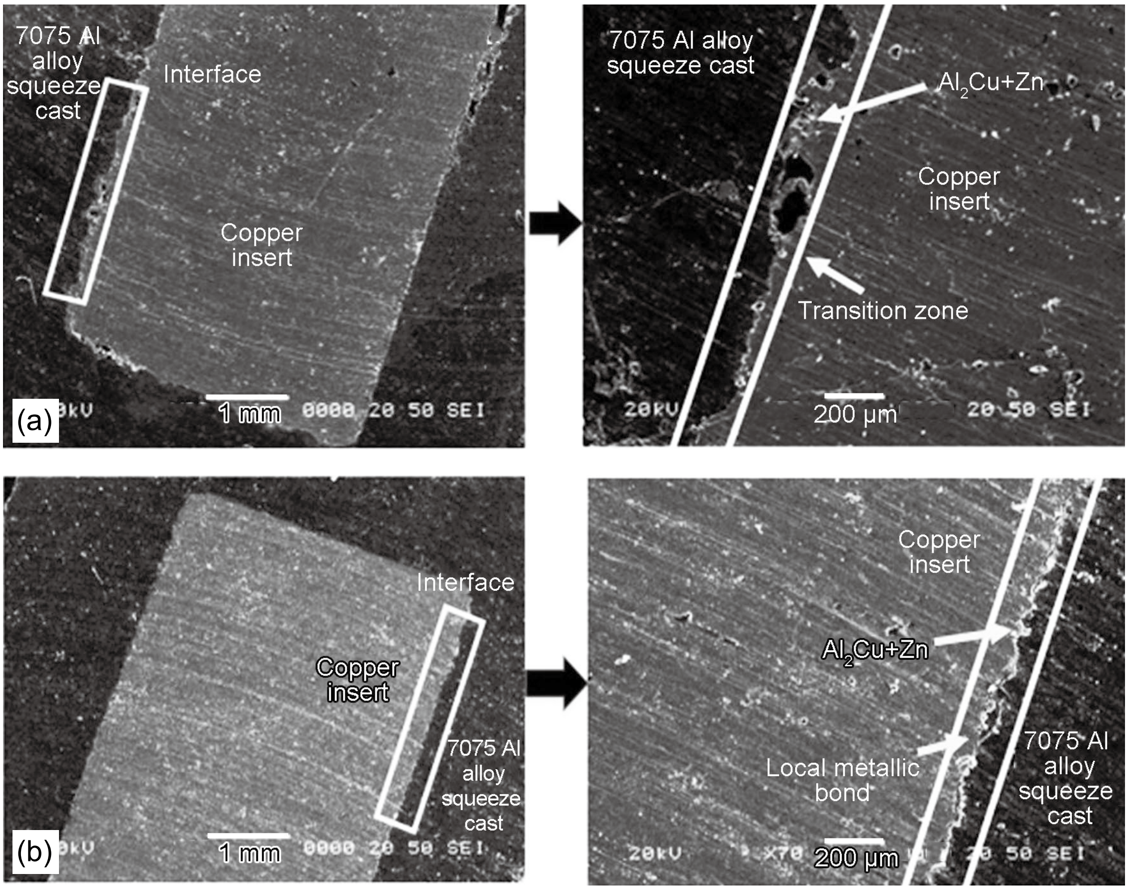


Fig. 8: Interface topography analysis of Al7075-Cu overcast joints at 750°C melt temperature, 60 MPa squeeze pressure and 150 °C die temperature (a); and 800 °C melt temperature, 90 MPa squeeze pressure and 250 °C die temperature (b)

note that increasing the squeezing pressure, die temperature, and melt temperature from a low to an optimal level has a significant positive effect on reducing defects in the manufacturing of squeeze overcast joints such as shrinkage cavities [7], premature solidification [15], and micro-cracks [8].

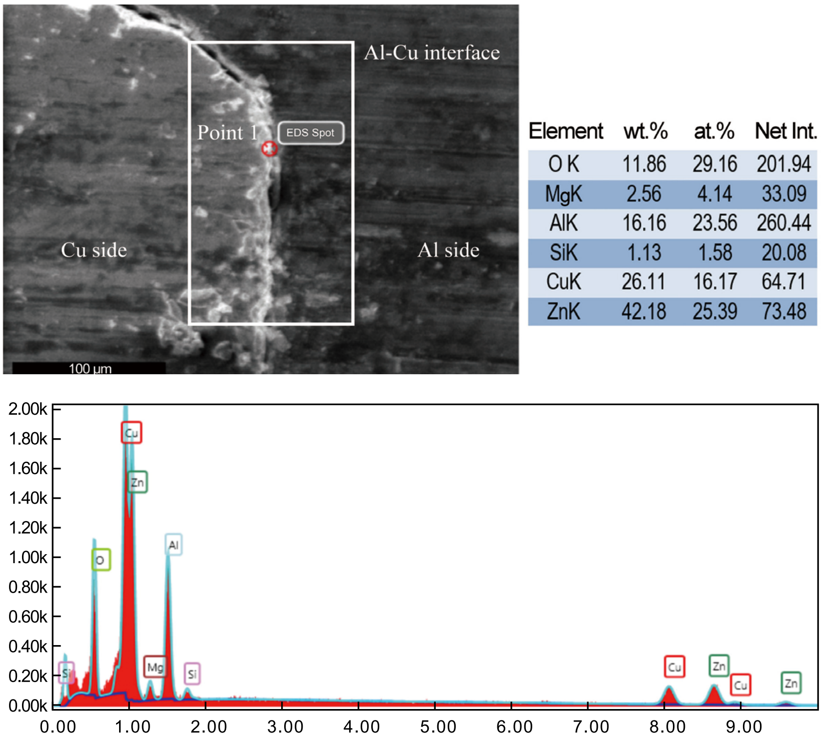
3.3.3 EDS analysis

Compositional analysis of the flat interface of Al7075-Cu overcast joint was performed at two experimental conditions using the EDS methods to further examine the effect of the process parameters. Figure 9 shows that poor melting of Zn coating (25.39at.%) in the interface region of Al7075-Cu overcast joint at a low level of process parameters causes the insufficient wettability between Al7075 squeeze cast material and solid Cu insert. This poor melting of the Zn coating causes low hardness and low UTS. While, strong intermetallic bonding is formed at 800 °C melt temperature, 90 MPa squeeze pressure, and 150 °C die temperature due to appropriate melting of Zn coating (15at.%), as depicted in Fig. 10. As a result, higher UTS (48 MPa) and hardness (76 HRB) are achieved under this experimental condition. Additionally, the Al_2Cu eutectic phase is formed at a high level of process parameters because of a great number of Cu atoms disperse into the Al melt during the solidification process, and the Al_2Cu+Zn phase formed at low level of process parameters due to the poor melting of Zn coating, as shown in Table 12. The Al-Cu overcast joint transition zone can be divided into the Cu-rich aluminum solid solution region, Al and Cu eutectic region, and Al and Cu intermetallic region [15]. According to Liu et al. [15], the crystallographic structures of the Al_2Cu eutectic phase are tetragonal. Furthermore, Murray et al. [24] found that the Al-Cu binary phase diagram consists of three different layers with the composition of Al_2Cu, Al-Zn eutectic, and Al-Cu, respectively.

4 Multi-response grey relational optimization

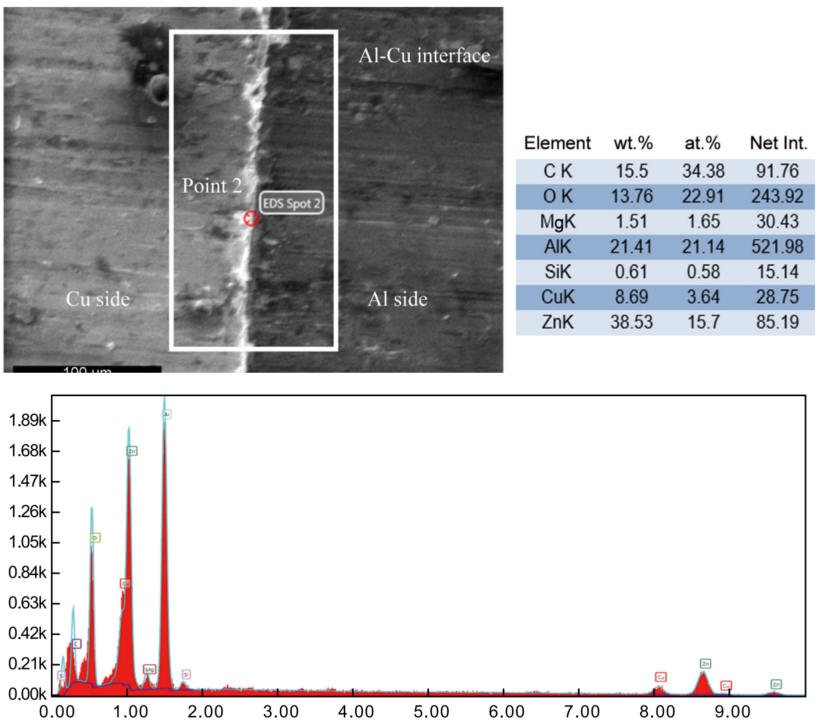
The larger the better condition was used for normalizing UTS and hardness. The normalized data is listed in Table 13. The grey relational grade (GRG) and grey relational coefficient values for all experiments are given in Table 14. Overall, the S/N ratio of GRG and mean are given in Tables 15 and 16, respectively, which were calculated using the larger the better condition. The main effect plots for the S/N ratios are depicted in Fig. 11, which graphically represents the influence of process-controlled variables on the multi-performance.

In this study, the GRG characterized all the mechanical parameters selected as output parameters. A higher grade refers to a close-to-optimal combination of the factors. It can be found



Element	wt.%	at.%	Net Int.
O K	11.86	29.16	201.94
MgK	2.56	4.14	33.09
AlK	16.16	23.56	260.44
SiK	1.13	1.58	20.08
CuK	26.11	16.17	64.71
ZnK	42.18	25.39	73.48

Fig. 9: EDS analysis at interface of Al7075-Cu overcast joints manufactured at 60 MPa squeeze pressure, 750 °C melt temperature, and 150 °C die temperature



Element	wt.%	at.%	Net Int.
C K	15.5	34.38	91.76
O K	13.76	22.91	243.92
MgK	1.51	1.65	30.43
AlK	21.41	21.14	521.98
SiK	0.61	0.58	15.14
CuK	8.69	3.64	28.75
ZnK	38.53	15.7	85.19

Fig. 10: EDS analysis at interface of Al7075-Cu overcast joints manufactured at 850 °C melt temperature, 90 MPa squeeze pressure, and 150 °C die temperature

Table 12: EDS results at selected points in specimen

Points	at.% Cu	at.% Al	at.% Zn	Possible phase
1	16.17	23.56	25.39	Al_2Cu+Zn
2	3.64	21.14	15.7	Al_2Cu

from Fig. 11 that the optimal values of hardness (76 HRB) and ultimate tensile strength (48 MPa) were achieved at Level 2 (800 °C) of melt temperature, Level 3 (250 °C) of die temperature, and Level 2 (90 MPa) of squeeze pressure after a single-response optimization problem was created from a multi-response optimization problem.

Table 13: Original and normalized response

Experiments	Response values		Normalized response values	
	UTS (MPa)	Hardness (HRB)	UTS (MPa)	Hardness (HRB)
1	18	55	0	0
2	30	65	0.4	0.4
3	25	61	0.2333	0.24
4	38	68	0.6666	0.52
5	48	76	1	0.84
6	32	69	0.4666	0.56
7	30	71	0.4	0.64
8	32	80	0.4666	1
9	29	72	0.3666	0.68

Table 14: Gray relation grade calculations

Experimet No.	UTS (MPa)	Hardness (HRB)	Gray relation grade	Rank
1	18	55	0.333333333	9
2	30	65	0.454545455	7
3	25	61	0.395781119	8
4	38	68	0.555102041	3
5	48	76	0.878787879	1
6	32	69	0.507892931	6
7	30	71	0.517970402	5
8	32	80	0.741935484	2
9	29	72	0.525466284	4

Table 15: Response S/N ratios for gray relation coefficients

Level	Squeeze pressure	Melt temperature	Die temperature
1	−8.147	−6.790	−6.007
2	−4.040	−3.521	−5.850
3	−4.632	−6.508	−4.962
Delta	4.107	3.268	1.044
Rank	1	2	3

Table 16: Response means for gray relation coefficients

Level	Squeeze pressure	Melt temperature	Die temperature
1	0.3946	0.4688	0.5277
2	0.6473	0.6918	0.5117
3	0.5951	0.4764	0.5975
Delta	0.2527	0.2230	0.0858
Rank	1	2	3

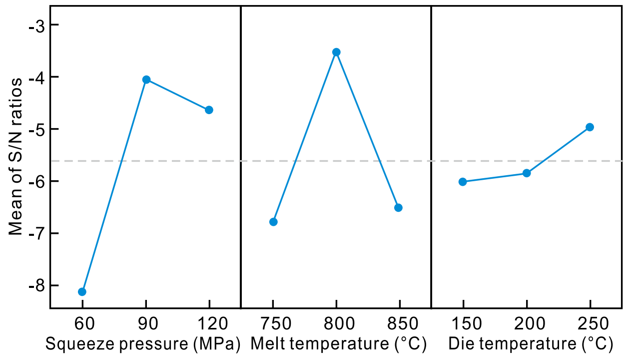


Fig. 11: Main effect plots of S/N ratio for grey relational grade

5 Confirmatory test

Confirmatory tests were carried out to corroborate the predicted results against the experimental values, as shown in Table 17. Therefore, the estimated GRG value (Y_{est}) at optimal conditions can be computed by the addition of the average response to the contribution of each factor at the optimal level [25, 26] using Eq. (1):

$$Y_{est}=Y_{avg}+(Y_{sopt}-Y_{avg})+(Y_{mopt}-Y_{avg})+(Y_{dopt}-Y_{avg}) \quad (1)$$

where Y_{avg} is the average grey relational grade (0.5456);

Table 17: Confirmatory test results of grey relational grade

Responses	Initial combination (Exp. No. 1)	Optimal conditions	
	Exp. value	Pred. value	Exp. value
UTS (MPa)	18		48
Hardness (HRB)	55		76
GRG	0.3330	0.8454	0.8787
Improvement in GRG		0.5487 (62.4%)	
Difference between Pred. and Exp.		0.0333 (3.8%)	

Y_{sopt}, Y_{mopt}, and Y_{dopt} are the average grey relational grades for squeeze pressure at its optimal level (0.6473), melt temperature at its optimal level (0.6918), and die temperature at its optimal level (0.5975), respectively.

Table 17 shows that predicted (Pred.) and experimental (Exp.) GRG values are close to each other, and experimental results validate the optimization of Al-Cu overcast joint parameters by employing the Taguchi-based GRA methodology. Furthermore, the GRG value has been improved (62.4%) from the initial combination of process parameters to the optimal combination. Hence, the Taguchi-based GRA method has improved the mechanical properties of the Al7075-Cu overcast joint.

6 Conclusions

Sound squeeze overcast Al7075-Cu joints were produced through an electro-plating process on the layer of Zn on a solid Cu insert. The squeeze overcast process parameters were optimized using the Taguchi-based GRA method, and the following conclusions are obtained:

(1) ANOVA results show that all parameters remarkably influence hardness and UTS. Squeeze pressure has the highest contribution followed by die and melt temperature, respectively. The optimum values of the UTS (48 MPa) and hardness (76 HRB) of squeeze overcast Al7075-Cu joint are achieved at the melt temperature of 800 ºC, die temperature of 250 ºC, and squeeze pressure of 90 MPa.

(2) The main effects plot analysis shows that UTS increases with the increase in squeeze pressure and melt temperature up to the middle level and then decreases with further increases of these two process parameters. Hardness increases with a rise in squeeze pressure, but it increases with an increase in melt temperature up to the middle level and then decreases with a further increase in melt temperature.

(3) Die temperature also affects the mechanical properties of squeeze overcast Al7075-Cu joints. As the die temperature increases, the UTS and hardness increase because casting defects such as cold shut can be eliminated at a high die temperature.

(4) Interface topography analysis reveals that the contact area between Al7075 alloy and solid copper insert increases with a rise in squeeze pressure from 60 to 90 MPa, and the compact microstructure of the Al7075-Cu overcast joint can be obtained at optimal experimental settings.

(5) The microstructural analysis of the squeeze overcast Al7075-Cu joints depicts that brittle fractures change from a cluster-like morphology to a flatter face with the increase of melt temperature and squeeze pressure from low to middle level. The EDS analysis results show that the Al_2Cu intermetallic phase is observed at the optimal experimental conditions, and the Al-Zn eutectic phase is observed at a low level of process parameters.

(6) The confirmation test reveals that the Taguchi base GRA method has significantly improved the hardness and ultimate tensile strength.

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Conflict of interest

The authors have no conflicts to declare.

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