ANALYZING THE EFFECT OF SQUEEZE CASTING PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF OVERCAST ALUMINIUM-ALLOY JOINT USING RESPONSE SURFACE METHODOLOGY

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ABSTRACT

This study contains, the overcast 2024-2024 wrought aluminium alloy joints produced by casting liquid 2024 wrought aluminium alloy onto the solid 2024 wrought aluminium alloy inserts using squeeze casting process. The quality of overcast joints fabricated via squeeze casting depend on mechanical properties such as ultimate tensile strength and yield strength. Mechanical properties depends upon the input casting parameters named as squeeze pressure, pressure duration and melt temperature. Response surface methodology (RSM) was employed to analyze the effect of above mentioned input parameters on ultimate tensile strength (UTS) and yield strength (YS). Empirical models for UTS and YS were developed which help the practitioners to achieve desired UTS and YS by using optimum vales of input parameters. ANOVA results shows that melt temperature has most significant effect on UTS and YS followed by squeeze pressure and pressure duration. Current study will provide efficacious approach to develop advance functional and structural materials.

KEYWORDS: *Overcasting, squeeze casting, response surface methodology, wrought aluminium alloy 2024, Zn electroplating*

INTRODUCTION

Aluminium metal castings are extensively used to take the advantage of their low density, corrosion resistance, formability, sufficient strength and permeability, in automotive and aerospace industries for light weight applications (Taub et al., 2007). Due to the up gradation of modern industry, it has become very challenging for one single metallic material to fulfil the firm demand of high efficiency and performance at low cost, since there are growingly jointing involved conditions (Hoeschl et al., 2006, Lloyd, 2013). Consequently, bimetallic design and fabrication looks to be a feasible solution (Lee et al., 2013, Zhang et al., 2014).

Materials have combination of desired properties can be generate by same and different materials joining. Numerous technical methods have been described in fabricating aluminium-aluminium bimetallic joints. These methods have been primarily classified into three categories: (1) solid-solid bonding, for example rolling (Lee et al., 2013), laser welding (Chang et al., 2010), brazing (Chang et al., 2009), explosive welding (Honarpisheh et al., 2012), friction stir welding (Xue et al., 2011), and hydrostatic extrusion (Lee et al., 2013); (2) solid-liquid bonding, for instance overcasting (Zhang and Chen, 2008, Rübner et al., 2011, Teng et al., 2015), and hot dipping (Yu et al., 2009); (3) liquid-liquid bonding, such as continuous casting (Sun et al., 2012, Wang et al., 2014).

Overcasting is well-defined; manufacturing technology by which two metals – one in solid form while the second one is in liquid form – came into contact so that a diffusion reaction zone generates between it, consequently a continuous metallic transition take place between metals, which is also known as compound casting or solid–liquid casting (Papis et al., 2008). In overcasting, metallurgical formation of interface zones is a basic key for joining solid and liquid metals due to the diffusion of liquid alloy's parts into the solid material partly through the development of solid solutions and reaction phases (Papis et al., 2008). Due to the mass saving, design flexibility, low fabricating cost and high manufacturing efficiency, overcasting has gained a huge importance in variety of systems, for example aluminium alloy and copper (Lee et al., 2013), aluminium alloy and steel (Liu et al., 2006), Al-alloy and Fe-alloy (Viala et al., 2002), and Mg-alloy and Al-alloy (Xu et al., 2014). However, this method has still very limited applications in aluminium alloys, because solid Al-alloys are always naturally enclosed in an aluminium oxide layer; inert and thermodynamically stable, while the melting point of this aluminium oxide

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film is much greater than the process temperature of the melt, thus not wettable easily by metallic melts (Papis et al., 2008). This aluminium oxide film cannot dissolved during the casting process and averts the formation of a metallic bonding between cast alloy and solid substrate. (Papis et al., 2008) developed a favorable method of joining aluminium alloys with replacing the aluminium oxide film by electroplating with zinc and couples of aluminium-magnesium substrates and various aluminium alloys were fabricated successfully. Besides zinc is appropriate as a coating material because of its low melting temperature of 420^{o}C and highly solubility in aluminium at elevated temperature. Based on the Papsi's approach (Rübner et al., 2011, Koerner et al., 2014) fabricated the aluminium-aluminium overcast joints by high pressure die casting.

However, limited studies have been reported on the wrought aluminium alloy-wrought aluminum alloy overcast joints, because when wrought aluminum alloys are used in casting process then a lot of casting defect such as shrinkages, porosities and cracks produced because of long solidification ranges and high heat crack trend (Hajjari and Divandari, 2008).While, many wrought aluminum alloys have been successfully fabricated directly into shape by squeeze casting process. Squeeze casting is a modern casting technique, in which melt is solidified under high applied pressure, and also considered such as a combination of forging and die casting (Ghomashchi and Vikhrov, 2000), high pressure applied eliminates shrinkage or gas porosity which improves the mechanical properties of casted product (Durrant et al., 1997). Thus, squeeze casting generates better results in term of microstructure and mechanical properties than the conventional ones. Squeeze casting parameters which affect the mechanical properties of casting alloys and need to be optimized are squeeze pressure, pressure duration, melt temperature, time delay and die temperature (Ghomashchi and Vikhrov, 2000, Vijian and Arunachalam, 2007, Zhang et al., 2007, Patel et al., 2015, GC et al., 2016, Manjunath et al., 2016). Squeeze pressure, melt temperature are vital parameters affecting the mechanical properties of casting product (Amin and Mufti, 2012, Haider and Mufti, 2014, Liu et al., 2015, Liu et al., 2016, Liu et al., 2016). Pressure duration also influences the mechanical properties of casting alloy (Yong and Clegg, 2005, Vijian and Arunachalam, 2007, Patel et al., 2015). Least pressure duration results in incomplete solidification cause the poor strength while long pressure duration affects the die life and punch extracting problems and long cycle time (Chen et al., 2002).

However from literature, it is inferred that response surface methodology is most effective statistical tool to predict and optimize the output responses by setting optimal input parameters combination (Patel et al., 2015, GC et al., 2016, Sarfraz et al., 2017). Al-Cu (2000 series) alloys have better damage tolerance and high resistance to fatigue crack growth than the other series of Al-alloys, and these alloys are the prime alloys used in airframe structure (Williams and Starke, 2003).

Therefore, objective of current study is to fabricate the wrought aluminium alloy-wrought aluminium alloy overcast joint via squeeze casting and investigate the influence of squeeze casting process parameters including; squeeze pressure, pressure duration and melt temperature on the mechanical properties of overcast Al-alloy joints and to develop an empirical relationship to predict the mechanical properties.

MATERIALS AND METHODS

This section briefly describes the material composition selected for solid inserts and casting material, surface treatment on solid inserts, experimental setup, sample making and mechanical testing and response measurement. 2024 wrought aluminium alloy was selected for both solid inserts and casting material. The chemical composition of the material is shown in table 1, it was measured by optical emission spectrometer.

Before the squeeze casting process, the 2024 wrought aluminium alloy solid inserts were formed with a dimensions 90 mm × 13 mm × 4 mm and surface of solid inserts was improved by abrasive paper. While, in order to remove the lubricants reminders and oxide layer from solid inserts, for eliminate reoxidation possibility, several surface pretreatments chemically including degreased, alkali erosion, acid pickling, first zinc treatment and second zinc treatment were subjected to solid inserts. After chemical treatment at solid inserts, electroplating method was then operated onto the 2024 wrought aluminium solid inserts to develop a uniform thickness of 7μm of zinc layer. Squeeze casting was carried out using 100 Ton hydraulic press as shown in fig 1.

Table 1: Chemical composition of wrought Al-alloy 2024

Elements	Cu	Mg	Mn	Ti	Ni	Si	Al
Weight %	3.85	1.19	0.59	0.02	0.03	0.16	94.16

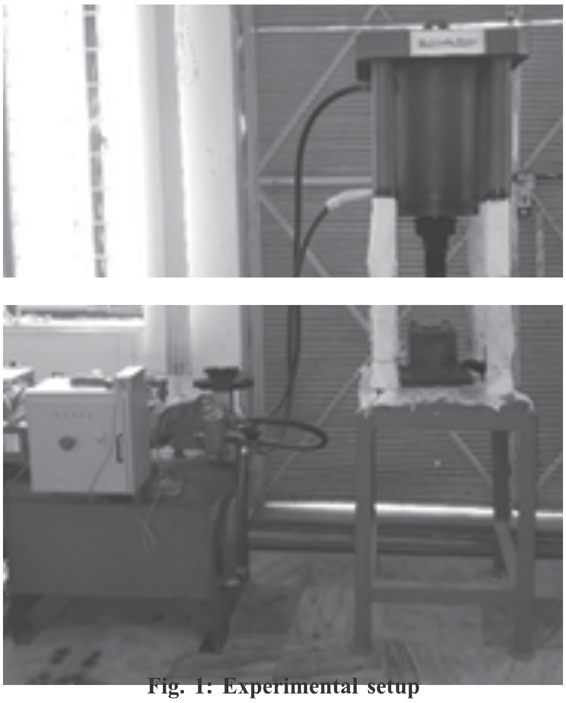

Fig. 1: Experimental setup

Three casting parameters; squeeze pressure, pressure duration and melt temperature were used for current study, while die preheating was used as a constant parameter. Melt temperature was attained though electric furnace having maximum temperature range 1200°C at 5000 W, pressure duration was measure with a stopwatch and die temperature achieved via oxyacetylene torch, measured by using infrared thermometer (SMART SENSOR :AR330). Die was pre-heated at 250°C, before squeeze casting process, electroplated solid insert was pre-placed with ejection pin at the base plate of the die, and then 2024 melt was poured into pre-heated die and solidified under applied pressure. 2024-2024 overcast joint was fabricated by squeeze casting, squeeze cast billets shown in fig 2.

Fig. 1: Experimental setup

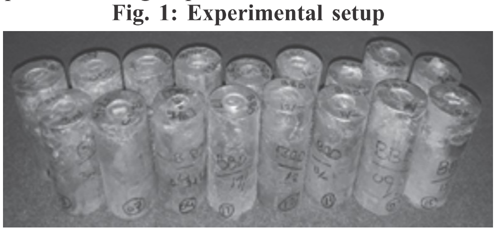

Fig. 2: Squeeze cast billets

Tensile samples were took from the center of billet according to ASTM: E8/E8M-11 standard. Tensile specimens shape was made on milling machine while parting was done at EDM Die Sink. Tensile specimen is shown in fig 3. Tensile testing was done at MTS-810 material testing system having 100 KN capacity to measure the ultimate tensile strength and yield strength at a strain rate of 0.005 mm/s and at ambient temperature.

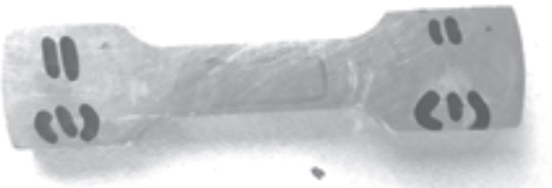

Fig. 3: Tensile specimen

EXPERIMENTAL DESIGN

For the current study, squeeze pressure (SP), pressure duration (PD) and melt temperature (MT) have been chosen as squeeze casting process parameters. Process parameters and ranges are shown in table 2.

Table 2: Squeeze casting input parameters and their levels

Process Parameters	Levels		
	Low	Medium	High
Squeeze Pressure (MPa)	50	90	130
Melt Temperature (°C)	750	800	850
Pressure Duration (sec)	60	120	180

The influence of squeeze casting process parameters on the mechanical properties of 2024-2024 overcast joints was analyzed and modelled by response surface methodology (RSM) with Box-Behnken design (BBD). Seventeen experiments were completed using three input parameters each at three levels, while center points were five. Table 3 presents the experimental design matrix with input process parameters and observed responses results.

Table 3: Experimental design matrix with response results

Sr. No.	Squeeze pressure	Melt temperature	Pressure duration	UTS	YS
	MPa	°C	Sec	MPa	MPa
1	90	750	60	195	117
2	50	850	120	229	133
3	130	800	180	231	136
4	90	800	120	261	154
5	130	750	120	196	114
6	90	800	120	259	152
7	50	800	60	220	129
8	90	800	120	257	151
9	50	800	180	224	128
10	90	850	180	225	134
11	90	800	120	254	148
12	130	850	120	242	141
13	90	800	120	262	158
14	90	750	180	201	118
15	90	850	60	226	131
16	50	750	120	198	115
17	130	800	60	227	132

RESULTS AND DISCUSSIONS

Development of Mathematical Models

Response variables (ultimate tensile strength and yeild strength) have been modeld using regression analysis with the help of comercial software. Analysis of variance ANOVA has been employed to examine the adequacy of emperical model.

Ultimate Tensile Strength

Quadratic relationship has been selected on the basis of fit summary of the UTS.Significant model terms: B (melt temperature) as main effect and A^2 (squeeze pressure), B^2 (melt temperature) and C^2 (pressure duration) as quadratic effects, are highlighted by the ANOVA results. ANOVA table shows the values of R^2, adjusted R^2 and predicted R^2 close to 1 which inferred the adeequacy of the model. The ultimate mathmatical model for the prediction of UTS has been presented in Eq 1.

UTS =-7265.075+0.186 × Squeeze Pressure+18.18325 × Melt Temperature+1.747 × Pressure Duration+1.875E-003 × Squeeze Pressure × Melt Temperature+0.0001 × Squeeze Pressure ×Pressure Duration-5.833E-004 × Melt Temperature × Pressure Duration-8.937E-003 × Squeeze Pressure2-0.0112× Melt Temperature2-5.222E-003 × Pressure Duration2 (1)

Yield Strength

ANOVA results shows the main and quadratic effects of the model which affects the YS significantly are; B (melt temperature), A^2 (squeeze pressure), B^2 (melt temperature) and C^2 (pressure duration). While the values of R^2, adjusted R^2 and predicted R^2 are close to 1 according to the ANOVA results which indicates the adequacy of the model. Whereas p-value is less than 0.05, which shows significance of the model. Eq 2 shows mathematical model for the prediction of YS.

YS =-4234.731+0.252 × Squeeze Pressure+10.658 × Melt Temperature+0.571 × Pressure Duration+1.125E-003 × Squeeze Pressure × Melt Temperature+5.208E-004× Squeeze Pressure × Pressure Duration+1.667E-004 × Melt Temperature × Pressure Duration-6.437E-003 × Squeeze Pressure2-6.62E-003 × Melt Temperature2-3.069E-003 × Pressure Duration2 (2)

Table 4: Analysis of variance (ANOVA) results of UTS and YS

Source UTS	Sum of Squares	df	Mean Square	F Value	p-value Prob > F		Source YS	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	8604.52	9	956.05	64.38	< 0.0001	significant	Model	3123.60	9	347.06	28.43	0.0001	signifi-cant
A-Squeeze Pressure	78.12	1	78.12	5.26	0.056		A-Squeeze Pressure	40.5	1	40.5	3.31	0.111	
B-Melt Tempera-ture	2178	1	2178	146.66	< 0.0001		B-Melt Tempera-ture	703.125	1	703.12	57.59	0.0001	
C-Pressure Duration	21.12	1	21.12	1.42	0.272		C-Pressure Duration	6.125	1	6.125	0.50	0.502	
AB	56.25	1	56.25	3.78	0.093		AB	20.25	1	20.25	1.65	0.238	
AC	0	1	0	0	1.00		AC	6.25	1	6.25	0.51	0.497	
BC	12.25	1	12.25	0.82	0.394		BC	1	1	1	0.081	0.783	
A2	861.01	1	861.01	57.98	0.0001		A2	446.69	1	446.69	36.59	0.0005	
B2	3312.85	1	3312.85	223.08	< 0.0001		B2	1153.27	1	1153.27	94.47	< 0.0001	
C2	1488.16	1	1488.16	100.21	< 0.0001		C2	514.11	1	514.11	42.11	0.0003	
Residual	103.95	7	14.85				Residual	85.45	7	12.20			
Lack of Fit	62.75	3	20.91	2.03	0.252	not signifi-cant	Lack of Fit	30.25	3	10.08	0.73	0.585	not sig-nificant
Pure Error	41.2	4	10.3				Pure Error	55.2	4	13.8			
Cor Total	8708.47	16					Cor Total	3209.05	16				
Std. Dev.	3.85	R-Squared	0.988	Std. Dev.	3.493872	R-Squared	0.973						
Mean	229.82	Adj R-Squared	0.972	Mean	134.7647	Adj R-Squared	0.939						
C.V. %	1.67	Pred R-Squared	0.877	C.V. %	2.592572	Pred R-Squared	0.822						
PRESS	1068.37	Adeq Preci-sion	22.576	PRESS	570.25	Adeq Precision	13.938						

Response Surface Plots

The effects of input process parameters; squeeze pressure (SP), pressure duration (PD) and melt temperature (MT) on the observed parameters; ultimate tensile strength (UTS) and yield strength (YS) examine with the help of response surface graphs.

Ultimate Tensile Strength

Fig 4 explains the behavior of UTS affected with squeeze pressure and melt temperature. UTS enhanced as the squeeze pressure and melt temperature increases up to some extent than decreases on further increment in the squeeze pressure and melt temperature. It is clearly evident from the graph, melt temperature effects significantly as compared to squeeze pressure. According to the fig 5 which describes the behaviour of UTS effected by squeeze pressure and pressure duration. UTS has minimum value at bottom levels of squeeze pressure and duration of pressure and slightly inceaseses till the mid levels squeeze pressure and pressure duration and then UTS decrease up to the high levels of the squeeze pressure and duration of pressure applied. Fig 6 demontrate the trend of UTS, by increasing melt temperature and presure duration. UTS inreases with the increase in both inputs till certain level than further increment in input parameters effcts adversly on the UTS. It is evident from figure that melt temperature significantly affects the UTS rather than presure duration.

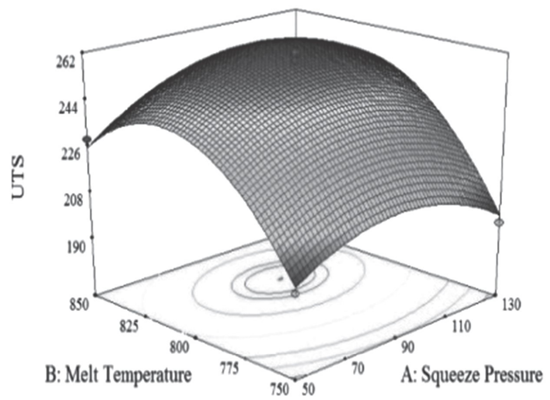

Fig. 4: Response surface plot of UTS between SP and MT

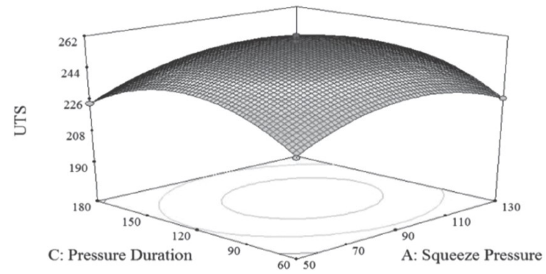

Fig. 5: Response surface plot of UTS between SP and PD

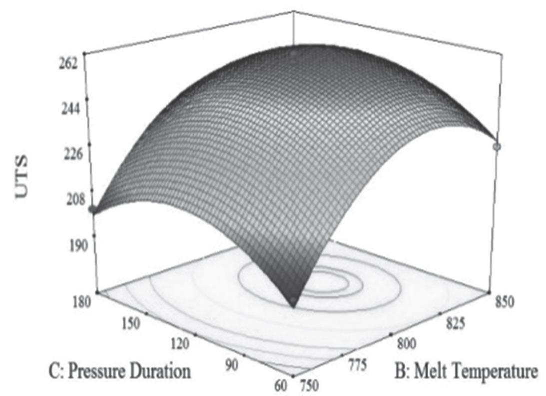

Fig. 6: Response surface plot of UTS between PD and MT

Yield Strength

Fig. 7 presents the trend of YS influenced with squeeze pressure and melt temperature. YS improved with enhancment in squeeze pressure and melt temperature till some limit than decreases on further increment in the squeeze pressure and melt temperature. It is clearly shown from the surface plot, melt temperature effects significantly as compared to squeeze pressure. According to the fig. 8 which shows the behaviour of YS effected by squeeze pressure and duration of applied pressure. YS has minimum value at bottom levels of squeeze pressure and its duration, while slightly inceaseses till the mid levels squeeze pressure and duration of pressure, then YS decrease up to the high levels of the squeeze pressure and duration of pressure applied. Fig. 9 illustrate the behaviour of YS, by increasing melt temperature and presure duration. YS inreases with the increase in both inpYS up to a certain level than further increament in input parameters vales effcts unfavorably on the YS. It is obvious from the figure that melt temperature significantly affects the YS rather than presure duration.

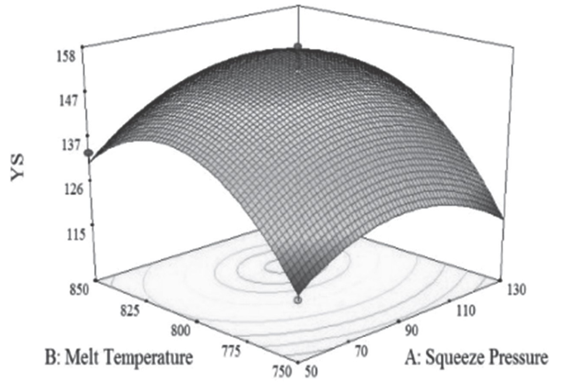

Fig. 7: Response surface plots of YS between SP and MT

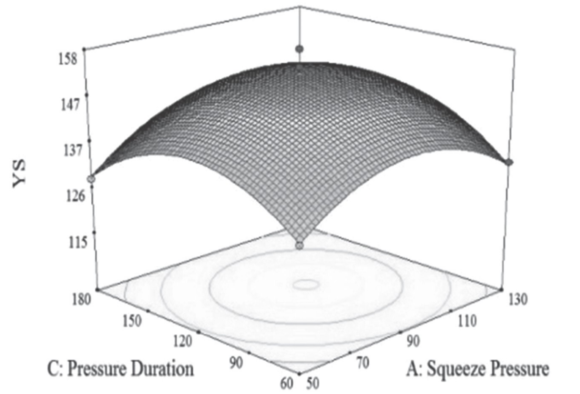

Fig. 8: Response surface plots of YS between SP and PD

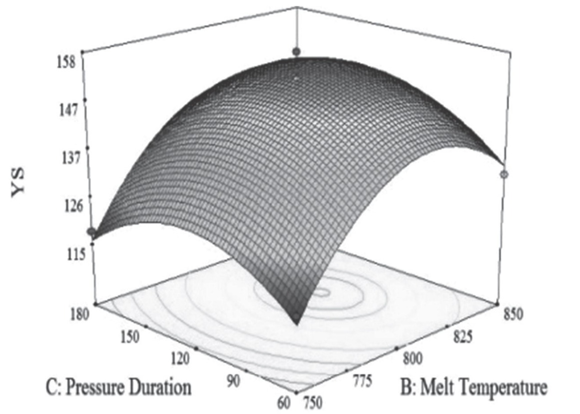

Fig. 9: Response surface plots of YS between PD and MT

Optimization

In this section optimization of each response is explained with the help of contour plots.

Ultimate Tensile Strength

Figure 10 contains the contour plot of the squeeze pressure vs melt temperature for UTS. Maximum value of UTS 261 MPa can be achived at 95 MPa squeeze pressure and 810°C melt temperature. Figure 11 contains the contour plot of the squeeze pressure vs pressure

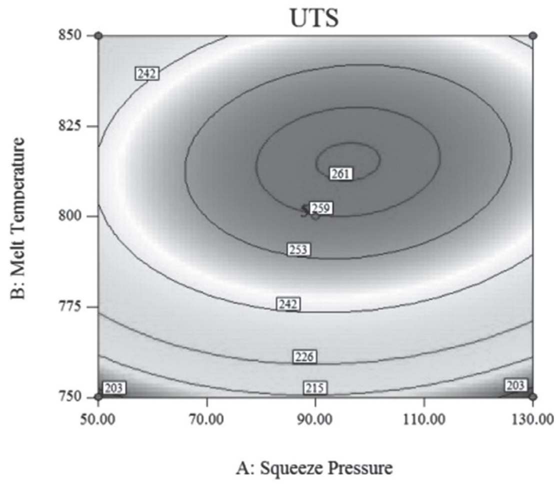

Fig. 10: Contour plot of UTS between SP and MT

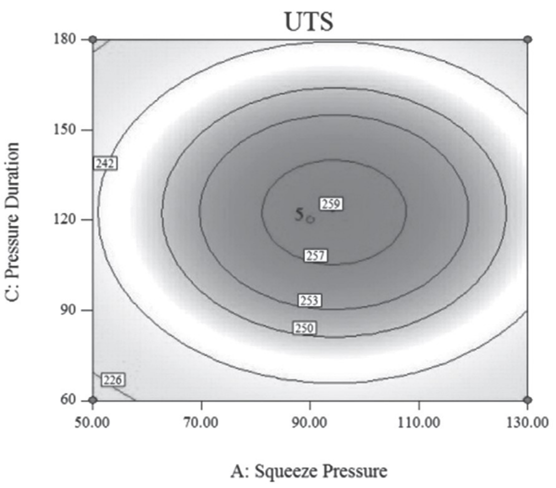

Fig. 11: Contour plot of UTS between SP and PD

duration for UTS. Maximum value of UTS 259 MPa can be achived at 97 MPa squeeze pressure and 127sec pressure duration. Figure 12 contains the contour plot of the pressure duration vs melt temperature for UTS. Maximum value of UTS 260 MPa can be achived at 109 sec pressureduration and 820°C melt temperature.

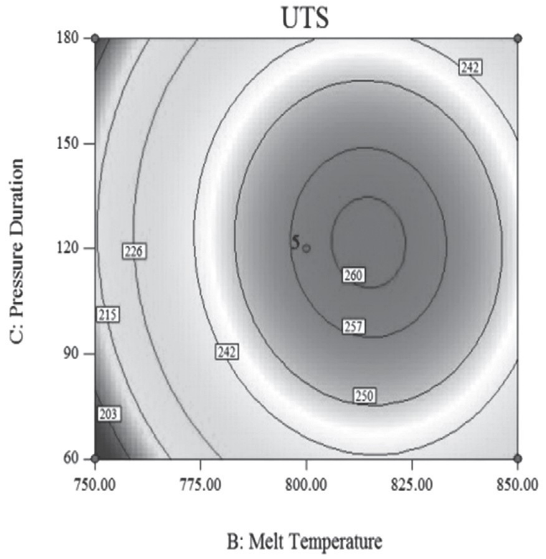

Fig. 12: Contour plot of UTS between PD and MT

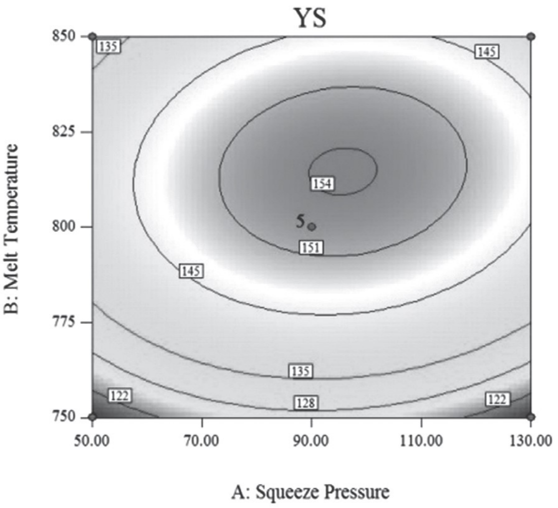

Fig. 13: Contour plot of YS between SP and MT

Yield Strength

Fig. 13 contains the contour plot of the squeeze pressure vs melt temperature for YS. Maximum value of YS 154 MPa can be achived at 97 MPa squeeze pressure and 805°C melt temperature. Fig. 14 contains the contour plot of the squeeze pressure vs pressure duration for YS. Maximum value of YS 152 MPa can be achived at 90 MPa squeeze pressure and 115 sec pressure duration. Figure 15 contains the contour plot of the pressure duration vs melt temperature for YS. Maximum value of YS 154 MPa can be achived at 120 sec pressure duration and 810°C melt temperature.

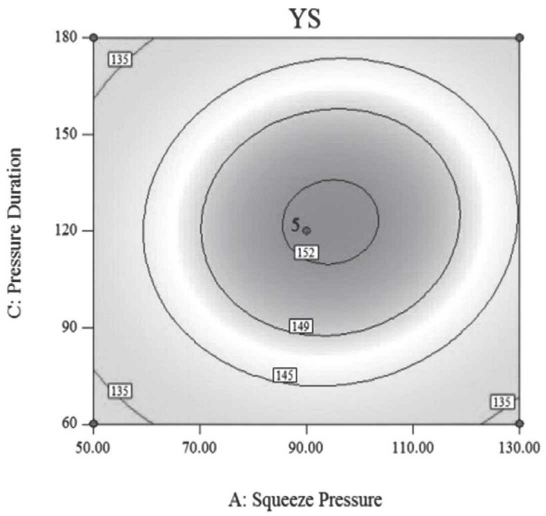

Fig. 14: Contour plot of YS between SP and PD

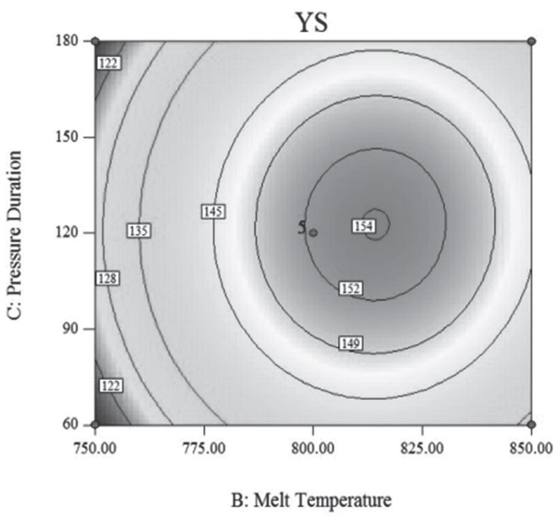

Fig. 15: Contour plot of YS between PD and MT

CONCLUSIONS

In this study, squeeze casting process was employed to fabricate the 2024-2024 overcast joints. The influences of squeeze casting process parameters; squeeze pressure,

pressure duration and melt temperature on the UTS and YS of overcast wrought aluminium alloy joints were examined and modelled using response surface methodology. Seventeen different experiments were performed with respect to the Box-Behnken design. Following conclusions were made from this study:

- Sound 2024-2024 overcast joints were fabricated successfully by electroplating of zinc on the 2024 aluminium alloy inserts and prudently controlling squeeze casting process.
- It was inferred that squeeze pressure, melt temperature and pressure duration significantly affects the mechanical properties of 2024-2024 overcast joints.
- It was found that at low level of SP, PD and MT, the value of UTS and YS were minimum. While with increase in SP, PD and MT up to certain level, the value of UTS and YS also increased, whereas on further increment in SP, PD and MT up to high level, the values of UTS and YS were decreased.
- Response surface plots demonstrated that melt temperature was most significant process parameters, which influencing the UTS and YS of overcast joint vitally. However, squeeze pressure and pressure duration slightly affects the UTS and YS as compare to melt temperature.
- The optimal level of process parameters were found in this research work at which better mechanical properties of overcast 2024-2024 alloy joints could be achieved.
- Mathematical models of UTS and YS will help the practitioners to set the input parameters according to their desired results.

ACKNOWLEDGMENT

The authors highly acknowledge University of Engineering and Technology Taxila for support and funding for this research work.

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