Investigating the effect of change in various process parameters on the mechanical properties of a brazement with Aluminium 6061 as the base material

[1]Teraiya Vijay, [2]Faizal Belim, [3]Dr. Pankaj Rathod, [4]Prof. Mitul Makwana
[12]Research Scholar of M.E., [34]Associate Professor,
[1234]Mechanical Engineering Dept.,
[1234]L.D.C.E., Ahmedabad, India.

Abstract : The aim of this Research to investigate the effect of variation in brazing parameters like clearance gap between base plates, scarf angle and soaking temperature on mechanical properties of brazed joint of Al 6061 plates. Brazing method used for investigation is torch (flame) brazing with oxy-LPG flame and Zn-18Al flux cored filler wire. Brazed joint tested for tensile strength and hardness. Multi-objective optimization was carried out. Results indicate that Clearance gap, scarf angle and soaking temperature have a significant effect on tensile strength, Hardness of joint and filler material consumption. Among Clearance gap, Scarf angle and Soaking temperature, the effect of scarf angle and clearance gap are more dominant. Values of tensile strength and hardness of joint are almost same as parent base material. Parameters that provides maximum tensile strength are Clearance gap 0.183 mm, scarf angle 57.18^o and soaking temperature 250.87^{o}C. Parameters that provides minimum hardness are clearance gap 0.298, scarf angle 85.67^{o}C and soaking temperature 296.33^{o}C. Parameters that provides maximum tensile strength, minimum hardness and minimum filler material consumption are Clearance gap 0.216 mm, scarf angle 63.79^o and soaking temperature 294.35^{o}C. These numerical optimization is carried out by software Design Expert Version 12.

Keywords- Brazing, Aluminium, Scarf angle, soaking temperature, Mechanical Properties, Numerical Analysis, Optimization

I. INTRODUCTION

The frequently preferred process for joining aluminium alloy is tungsten inert gas welding. However, this process causes grains to coarsen in the fusion zone, distortion, an increased tendency to undergo hot cracking and residual stresses.Brazing is utilized to eliminate the disadvantages of TIG welding. Brazing is a metal-joining technique where in a filler metal is used to join two or more materials by drawing it into the joint by capillary action. Brazing allows for more precise control of tolerances and provides a clean joint with no need for additional finishing Aluminium have wide range of other properties like light weight, good formability, favourable mechanical properties and electrical conductivity. In particular, 6000 series aluminium alloys have been studied extensively because they have better strength, weldability, corrosion resistance, and economical than other aluminium alloys. Due to these reasons aluminium alloys have wide range of applications in industries like aerospace, automobile industries, electrical circuits, heat exchangers and medical instruments. Therefore joining of aluminium alloy is important concern. Lots of efforts have been made in the previous years in developing different filler a. Wei Dai, Songbai Xue, Jiyuan Lou and Shuiqing Wang designed Ternary Al-Si-Zn fillermetals in order to join the 6061 aluminum alloy. The microstructure, phase constitution and fracture morphology of the brazed joint were investigated [1]. S.Y. Chang, L.C. Tsao, T.Y. Li, T.H. Chuang designed Al-Si-Cu filler materials and carried out brazing of Aluminium 6061 [2]. Jinlong Yang , SongbaiXue , PengXue , ZhaopingLv , WeiminLong , Guanxing Zhang , QingkeZhang , PengHe have conducted brazing of Al6061 to stainless steel 304 usingaZn–15Al–xZr filler metal and the effects of Zirconium(Zr) addition on the properties and microstructures of Zn–15Al filler metals were investigated. The experimental results indicated that the liquidus temperature of Zn–15Al– xZr was approximately 445 °C and Zr addition had little influence on the melting point of the Zn–15Al– xZr filler metal[3]. Dai Wei , Xue Songbai , Sun Bo , Lou Jiang , Wang Suiqing developed Al-Si-Zn filler metals containing Ti and Sr and which is used for brazing Al6061 The results indicate that the addition of Zn into the Al–Si filler metal lowers the solidus temperature from 583 °C to around 520 °C. The minor addition of modification element Sr and refine element Ti into Al-Si-Zn alloy will cause the remarkable modification of Al-Si eutectic and the α-Al phase is also refined[4]. Wei Dai, Song-bai Xue, Feng Ji, Jiang Lou, Bo Sun, and Shui-qing Wang developed Al-6.5Si-42Zn and Al-6.5Si-42Zn-0.09Sr filler metals which is used for brazing 6061 aluminum alloy. Air cooling and water cooling were applied after brazing. Si phase morphologies in the brazing alloy and the brazed joints were investigated[5]. Dai Wei1, Xue Song-Bai1, Lou Ji-Yuan, Lou Yin-Bin, Wang Shui-Qing were used torch brazing for brazing Al3003 using Al-Zn filler. Using Zn-Al filler metal with Al content of 2%-22% (mass fraction) and improved CsF-AlF3 flux, wetting properties of Zn-Al filler metal on 3003 Al substrate were investigated[6]. L.C. Tsao, M.J. Chiang, W.H. Lin, M.D. Cheng, T.H. Chuang have studied series of Al–Si–Cu–Zn alloys For the development of a low-melting-point filler metal for brazing aluminum alloys[7]. Fangfei Sui , Weimin Long , Shengxin Liu , Guanxing Zhang , Li Bao , Hao Li , Yong Chen have carried out induction brazing of 316LN stainless steel using Ag–Cu–Zn filler metal containing various content of Ca and investigate the influence of impurity element Ca on the microstructure and mechanical properties of the brazed joint. The results showed that Ca additions caused the coarser of the grains and their irregular distribution. Increase of the Ca content resulted in the formations of brittle intermetallic compounds (IMCs) CaCu which perhaps lead to the formations of voids[8]. L. Sisamouth, M. Hamd,T. Ariga have attempt to develop cadmium-free silver brazing filler metals, the ternary Ag–Cu–In alloys were investigated. The effect of varying indium content on melting temperatures and brazeability of Ag–Cu–In alloys on copper was ascertained in this article. Additionally, microstructures, hardness, and shear strength of the brazed joints were investigated[9]. Yaowu Shi, Yang Yu, Yapeng Li, Zhidong Xia, Yongping Lei, Xiaoyan Li, and Fu Guo have investigate the effect of adding small amounts of rare earth Er on the microstructure of an Al-Cu-Si brazealloy has been investigated. Several

Al-20Cu-7Si braze alloys containing various contents of Er were prepared, and their melting temperature, microstructure, hardness, and wettability in contact with 3003 aluminum alloy substrates were determined[10]. Yang Jinlong , Xue Songbai , Xue Peng , Lv Zhaoping , Dai Wei , Zhang Junxiong have developed novel CsF–RbF–AlF3 flux for aluminium brazing[11]. Bing Xiao , Dongpo Wang , Fangjie Cheng , YingWangIntermediate-temperature brazing of the 5052 aluminium alloy was conducted using Zn–xAl (x = 8, 15, and 22 wt.%) filler metals with a ZrF4-containing CsF–AlF3 flux developed in this study[12]. Haojiang Shi, Jiazhen Yan, Ning Li, Xin Zhu, Kangwei Chen, Lingfei Yu investigate the effect of brazing time and brazingtemperature on joint strength of brazing of FeCrMo damping alloy[13].Huei Lin, Jiun-Ren Hwang And Chin-Ping Fung have investigates how different process parameters affect the tensile properties of 6061-T6 aluminum vacuum brazed joints. The parameters including the soaking temperature, soaking time, brazing temperature, and brazing time were taken into consideration[14]. Arkan Kh. Al Taie and Alaa A. Ateia investigate the effects of clearance width on the tensile, bending and torsion strength of a low carbon steel butt weld joint. Experiments have proved that the joint strength increases with clearance width to reach a maximum value at a clearance width of (0.29-0.3mm)[15].

Literature review shows that lots of research work in field of brazing is done in filler material and flux material development. Effect of variation of Scarf angle, clearance gap between base plates and post brazing heat treatment on properties of brazement for Al6061 has not been studied.

II. EXPERIMENTAL SETUP AND METHODOLOGY

Experimental setup for the brazing of Al is shown in below Figure 1. As shown in figure, manual flame brazing method was used for the brazing purpose .Flame type is oxy-LPG. Base material selected is Al 6061 having size of 50 X 25 X 6 mm3.

Figure 1: Experimental setup of flame brazing (Heat source and nozzle)

Composition of Al 6061 is shown in Table 1. Filler metal used in this research is an alloy of Aluminium and Zinc. Filler wire is flux cored. The properties and composition of the filler wire is shown in Table 2 and Table 3. Filler wire $CsKAlF_4$ flux which is non-corrosive and non-toxic in nature. Before brazing process was carried out, both base plates were machined to required scarf angle. After that both plates were cleaned using aqueous cleaning technique. After that both plates were assembled in proper alignment with different geometric parameters and hold in their respective position by c clamp. Gap between two plates was measured with the help of filler gauge. The experiments were performed as by selecting different parameters. In this research, find the effect of variation in scarf angle, clearance gap and soaking temperature on mechanical properties of joint. Scarf angle, Clearance gap and Soaking temperature are variable parameters. After selecting variable parameter, three levels for each parameter were selected as shown in Table 4. Design of experiments performed by box-behnken method. It is an experimental design for response surface methodology. 15 experiments performed as per DOE. The design of experiment given by box-behnken method is shown in Table 5.

Table 1: Chemical compositions of base metal Al 6061

Element	Mg	Si	Cu	Cr	Mn	Zn	Ti	Fe	Al
% wt	0.56	0.410	0.001	0.12	0.008	0.009	0.008	0.1	98.83

Table 2: Properties of filler material

Type	**SU-TC 100**
Melting Temperature	425 – 490 ºC
Diameter	1.4 mm
Shape	Wire Shape

Table 3: Chemical compositions of filler material

Element	%wt
Al	18.53
Zn	81.27
Other Element	0.20

Table 4: Levels of the variables according to RSM

Parameters	Level -1	Level 0	Level 1
Clearance gap (d)	0.1	0.2	0.3
Scarf angle (θ)	30º	60º	90º
Soaking Temperature (T)	200 ºC	250 ºC	300 ºC

Table 5: Values of the variables of the matrix of experiments

Order	Coded Variable			Real Variable		
	Clearance gap "A"	Scarf Angle "B"	Soaking Temperature "C"	Clearance gap "d"	Scarf Angle "θ"	Soaking Temperature "T"
1	-1	-1	0	0.1	30º	250ºC
2	1	-1	0	0.3	30º	250ºC
3	-1	1	0	0.1	90º	250ºC
4	1	1	0	0.3	90º	250ºC
5	-1	0	-1	0.1	60º	200ºC
6	1	0	-1	0.3	60º	200ºC
7	-1	0	1	0.1	60º	300ºC
8	1	0	1	0.3	60º	300ºC
9	0	-1	-1	0.2	30º	200ºC
10	0	1	-1	0.2	90º	200ºC
11	0	-1	1	0.2	30º	300ºC
12	0	1	1	0.2	90º	300ºC
13	0	0	0	0.2	60º	250ºC
14	0	0	0	0.2	60º	250ºC
15	0	0	0	0.2	60º	250ºC

Specimen brazed according to the DOE is shown in Figure 2. Post brazing, joints are put in furnace which are heated from room temperature to required temperature (200oC, 250oC, 300oC) for 60 minutes and after that cooled in furnace (Annealing process). For grain growth and desirable results of testing 14 days time is given to specimens for natural ageing of aluminium and after that mechanical testing is carried out.

Specimens were tested for the ultimate tensile strength and hardness. The ultimate tensile strength of the joint was examined by Fie universal testing machine UTE 40. For hardness, Fie Vickers hardness tester VM 50 was used. To select optimum parameters for required strength and hardness, optimization and numerical analysis were performed using ANOVA.

III. RESULTS AND DISCUSSION

Result obtained from the experiment are shown in Table 6. To analyze this result and perform optimization of process parameters Design expert software version 12 was used for this purpose. Analysis of variance (ANOVA) has been performed to find the effects of each factors and their interactions with the responses. ANOVA provides an estimate of variance via the mean square of the residuals.

For ultimate tensile strength and hardness, mathematical model was developed to relating response and the factors to facilitate the optimization of the process.

Figure 2: Brazed specimens

Table 6: Experimental results of Ultimate Tensile strength, hardness

Std. order	Run	Input parameters			Output responses	
		A:Clearance Gap "d" (mm)	B:Scarf Angle "θ" (degree)	C:Soaking Temperature "T" (Celsius)	Tensile Strength (Mpa)	Hardness (HV)
1	3	0.1	30	250	108.348	96
2	13	0.3	30	250	107.543	85
3	8	0.1	90	250	104.886	95
4	14	0.3	90	250	103.442	83
5	1	0.1	60	200	115.568	93
6	2	0.3	60	200	112.846	82
7	10	0.1	60	300	116.786	92
8	4	0.3	60	300	111.458	81
9	15	0.2	30	200	108.931	89
10	12	0.2	90	200	104.884	88
11	11	0.2	30	300	109.545	89
12	5	0.2	90	300	104.222	86
13	7	0.2	60	250	120.346	90
14	9	0.2	60	250	121.448	88
15	6	0.2	60	250	121.543	89

3.1 Ultimate tensile strength

The second order Ultimate tensile strength model is developed using Response surface methodology (RSM) from the experimental results of Ultimate tensile strength (UTS), The final equation in terms of coded factors for UTS is given by,

$$UTS = +121.11 - 1.29*A - 2.12*B - 0.0273*C - 0.1597*AB - 0.6515*AC - 0.3190*BC - 3.89*A^2 - 11.16*B^2 - 3.05*C^2$$

Where A = clearance gap B=scarf angle and c=soaking temperature

The analysis of variance (ANOVA) and F-ratio test have been performed to justify the goodness of fit for the second order UTS model as shown in **table 7**. The Model F-value of 56.57 implies the model is significant. P-values less than 0.0500 indicate model terms are significant. Regression analysis of tensile strength is shown in **table 8** The "Predicted R^2" of 0.8659 is in reasonable agreement with the "Adjusted R^2" of 0.9728 as one might normally expect; i.e. the difference is less than 0.2. Reasonable agreement between these two terms of regression Pred R^2 and Adj R^2 shows that data obtained through the experimental investigations is properly fitted through the mathematical models obtained through the regression analysis. This implies that the model proposed is adequate and there is no reason to suspect any violation of the independent or constant variance assumption. Hence, the model can be used for further analysis to determine the effects of various process parameters on the response

Table 7: ANOVA for the Ultimate tensile stress model

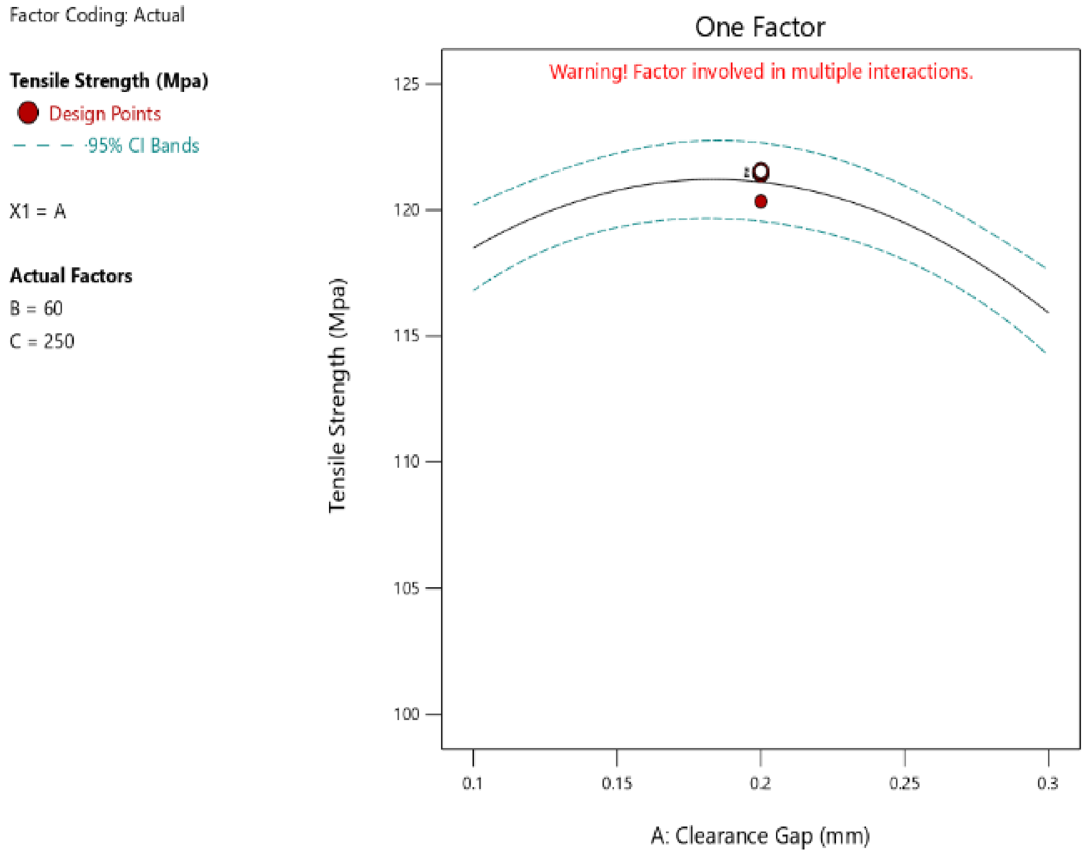
Source	Sum of Squares	DOF	Mean Square	F-value	p-value	Remarks
Model	560.28	9	62.25	56.57	0.0002	significant
A-Clearance Gap	13.26	1	13.26	12.05	0.0178	
B-Scarf Angle	35.84	1	35.84	32.57	0.0023	
C-Soaking Temperature	0.0059	1	0.0059	0.0054	0.9443	
AB	0.1021	1	0.1021	0.0928	0.7730	
AC	1.70	1	1.70	1.54	0.2693	
BC	0.4070	1	0.4070	0.3699	0.5696	
A^2	56.00	1	56.00	50.89	0.0008	
B^2	460.13	1	460.13	418.16	< 0.0001	
C^2	34.43	1	34.43	31.29	0.0025	
Residual	5.50	5	1.10			
Lack of Fit	4.62	3	1.54	3.48	0.2314	not significant
Pure Error	0.8854	2	0.4427			
Total	565.78	14				

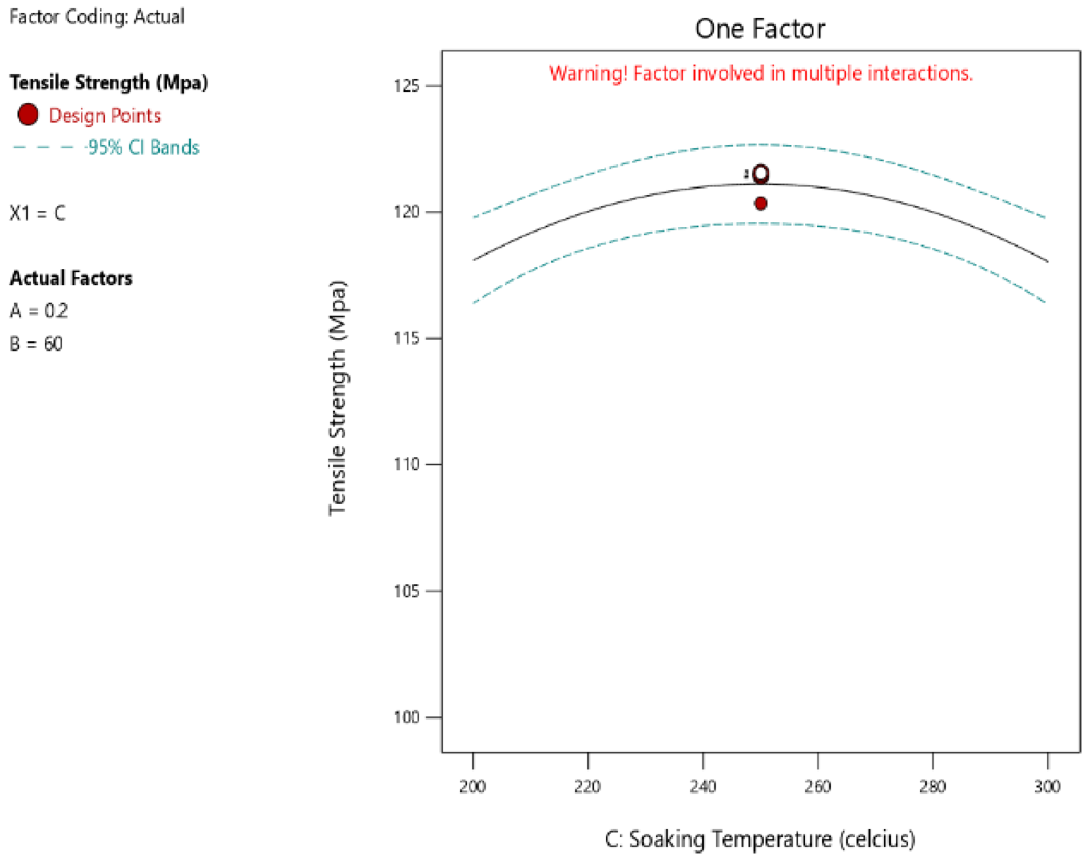
Table 8: Regression analysis of tensile strength Model

Std. Dev.	**1.05**	**R-Squared**	**0.9903**
Mean	111.45	**Adj R-Squared**	**0.9728**
C.V. %	0.9412	**Pred R-Squared**	**0.8659**
PRESS	**75.86**	**Adeq Precision**	**21.7413**

3.2 Effect of individual parameters on UTS

The effect of each individual parameter namely clearance gap, scarf angle and soaking temperature is shown in figure 3. For clearance gap, with increase in Clearance gap, Ultimate tensile strength increases first, then it becomes maximum, then it starts decreasing with increase in value of Clearance Gap. At lower Clearance gap, filler metal consumption is less and very thin joint take place and due to that strength of joint is slightly low. As clearance gap increase joint thickness is increase and strength of joint is also increase. For Larger clearance gap, capillary action is not take place properly due to that the value of Ultimate tensile strength decreases at higher clearance gap. Effect of scarf angle has similar effect like variation in clearance gap. With increase in scarf angle first tensile strength increase then become maximum and after that start decreasing with increase in value of scarf angle. This behaviour is observed in Figure. For low value of scarf angle failure is combined effect of tension and shear and due to that tensile strength is slightly reduced. At very high scarf angle joint area is reduced and due to that tensile strength is reduced


Factor Coding: Actual
Tensile Strength (Mpa)
Design Points
95% CI Bands
X1 = A
Actual Factors
B = 60
C = 250
One Factor
Warning! Factor involved in multiple interactions.
Tensile Strength (Mpa)
125
120
115
110
105
100
0.1
0.15
0.2
0.25
0.3
A: Clearance Gap (mm)


Factor Coding: Actual
Tensile Strength (Mpa)
Design Points
95% CI Bands
X1 = C
Actual Factors
A = 0.2
B = 60
One Factor
Warning! Factor involved in multiple interactions.
Tensile Strength (Mpa)
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120
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100
200
220
240
260
280
300
C: Soaking Temperature (celcius)

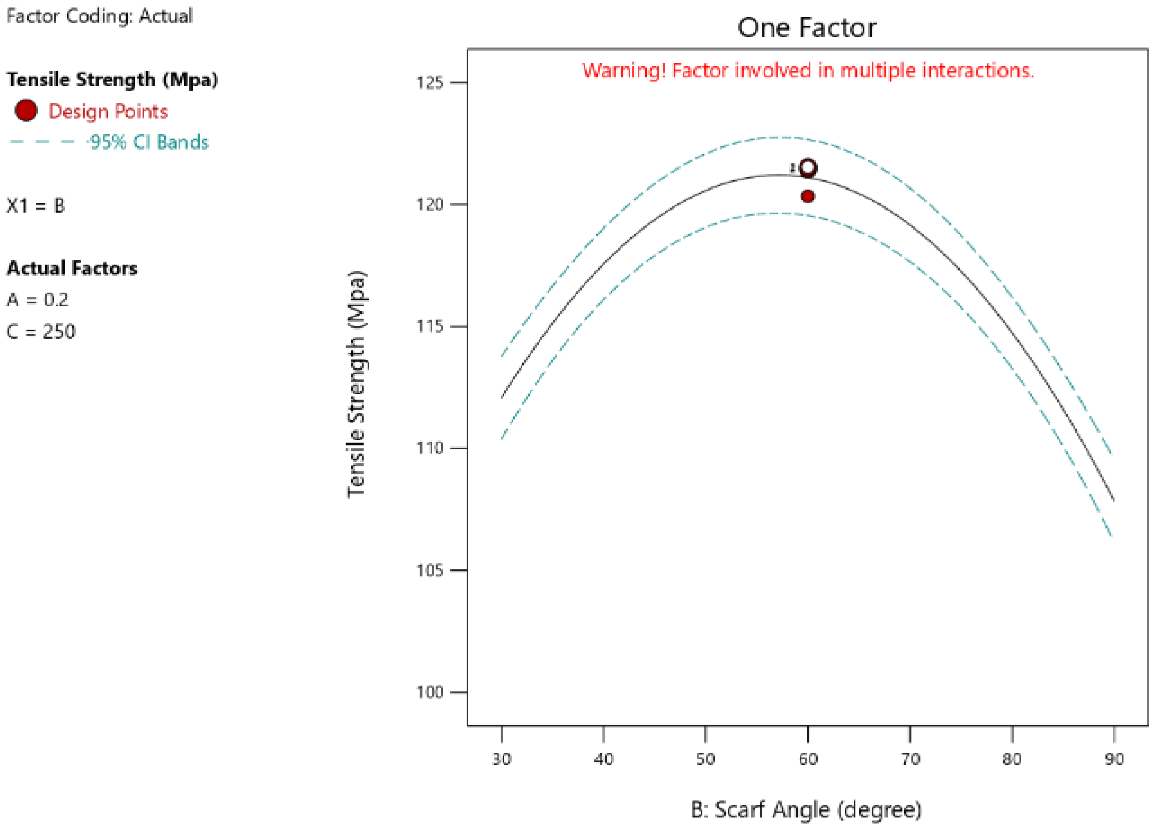


Figure 3: Effect of clearance gap, soaking temperature and clearance gap on UTS

For soaking temperature, the effect of increase in soaking temperature on tensile strength is less dominant. With increase in soaking temperature tensile strength is increase become maximum for value about 250oC and then slightly decrease with increase in soaking temperature. This behaviour can seen from figure 3.

3.3 Hardness

The second order model for hardness is developed using Response surface methodology (RSM) from the experimental results. The final equation in terms of coded factors for Hardness is given by,

$$Hardness = 89 - 5.625 * A - 0.875 * B - 0.5 * C - 0.25 * AB - 0.5 * BC - 0.125 * A^2 + 0.875 * B^2 - 1.875 * C^2$$

Where, A, B and C are coded variables for Clearance gap, scarf angle and soaking temperature respectively.

The analysis of variance (ANOVA) and F-ratio test have been performed to justify the goodness of fit for second order hardness model. ANOVA for hardness model shown in table 9. The Model F-value of 68.98 implies the model is significant. P-values less than 0.0500 indicate model terms are significant.

Regression model for hardness shown in table 10. The Predicted R^2 of 0.9698 is in reasonable agreement with the Adjusted R^2 of 0.9776;i.e. the difference is less than 0.2.Reasonable agreement between these two terms of regression Pred R2 and Adj R2 shows that data obtained through the experimental investigations is properly fitted through the mathematical models obtained through the regression analysis.

This implies that the model proposed is adequate and there is no reason to suspect any violation of the independent or constant variance assumption. Hence, the model can be used for further analysis to determine the effects of various process parameters on the response.

Table 9: ANOVA for the Hardness model

Source	Sum of Squares	DOF	Mean Square	F-value	p-value	Remarks
Model	279.35	9	31.04	68.98	0.0001	significant
A-Clearance Gap	253.13	1	253.13	562.50	< 0.0001	
B-Scarf Angle	6.13	1	6.13	13.61	0.0142	
C-Soaking Temperature	2.00	1	2.00	4.44	0.0888	
AB	0.2500	1	0.2500	0.5556	0.4896	
AC	0.0000	1	0.0000	0.0000	1.0000	

BC	1.0000	1	1.0000	2.22	0.1962	
A^2	0.0577	1	0.0577	0.1282	0.7349	
B^2	2.83	1	2.83	6.28	0.0541	
C^2	12.98	1	12.98	28.85	0.0030	
Residual	2.25	5	0.4500			
Lack of Fit	0.2500	3	0.0833	0.0833	0.9630	not significant
Pure Error	2.00	2	1.0000			
Total	281.60	14				

Table 10: Regression analysis of Hardness Model

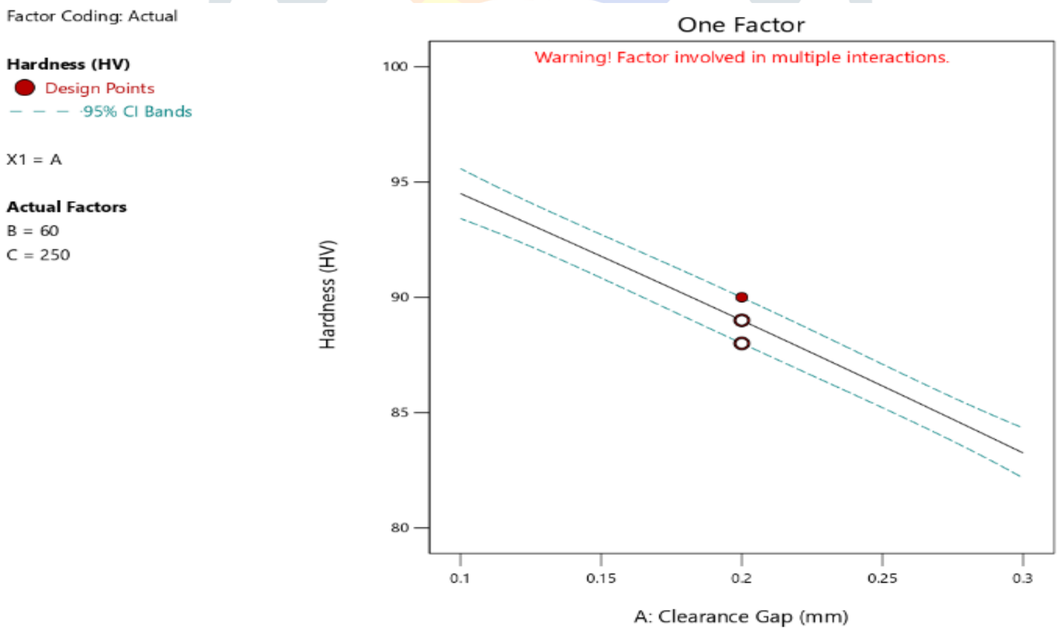
Std. Dev.	**0.6708**	R^2	**0.9920**
Mean	88.40	**Adjusted R^2**	0.9776
C.V. %	0.7588	**Predicted R^2**	0.9698
Press	8.50	**Adeq Precision**	27.6143

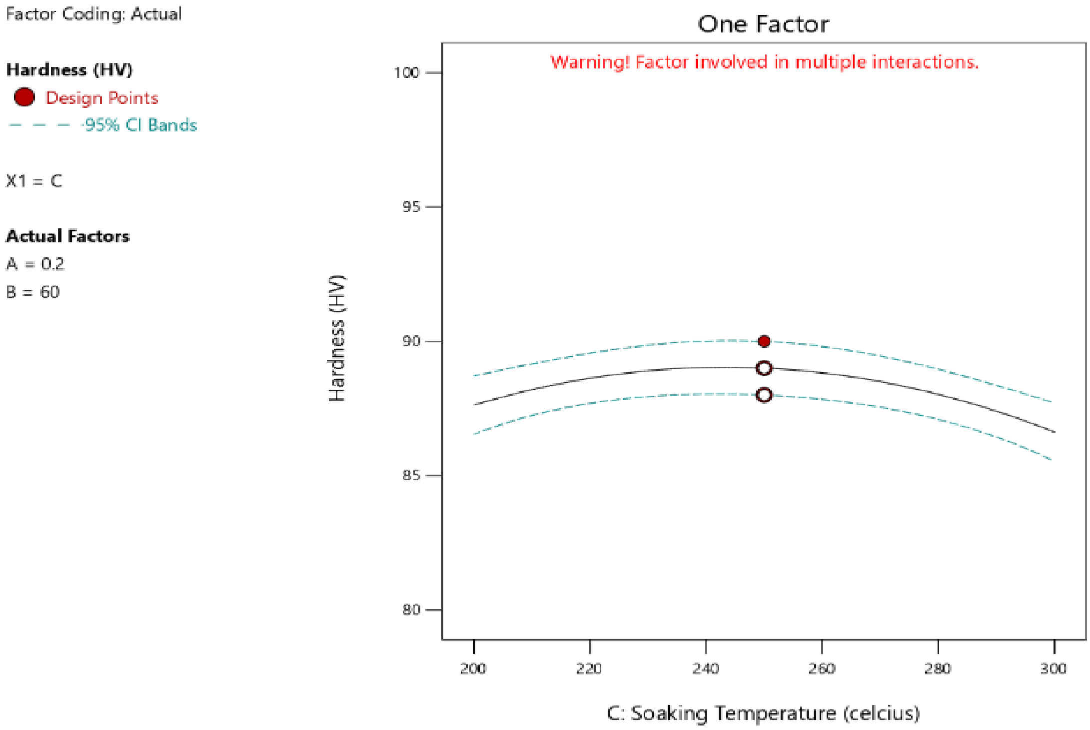
3.4 Effect of individual parameters on hardness

Effect of variable parameters on hardness is shown in figure individually. For clearance gap, As clearance gap is increase there is decrease in the hardness value of the joint. This behaviour is seen from the Figure. This happen due to hardness value of Filler (Zn-22Al) is around 90-100 HV while Hardness value of base metal is around 110-120 HV. As clearance gap increase joint is purely made of Zn-22Al.

For scarf angle, Scarf angle has negligible effect on the joint hardness value as shown in figure. Hardness value is almost same for scarf angle ranges from 30-90 degree. Slight variation in hardness value is due to noise and effect of other factors.

As shown in figure 4, the effect of increase soaking temperature on Hardness is not much dominant. Hardness value of brazed joint is almost same for entire range of soaking temperature which is chosen for these experiment.





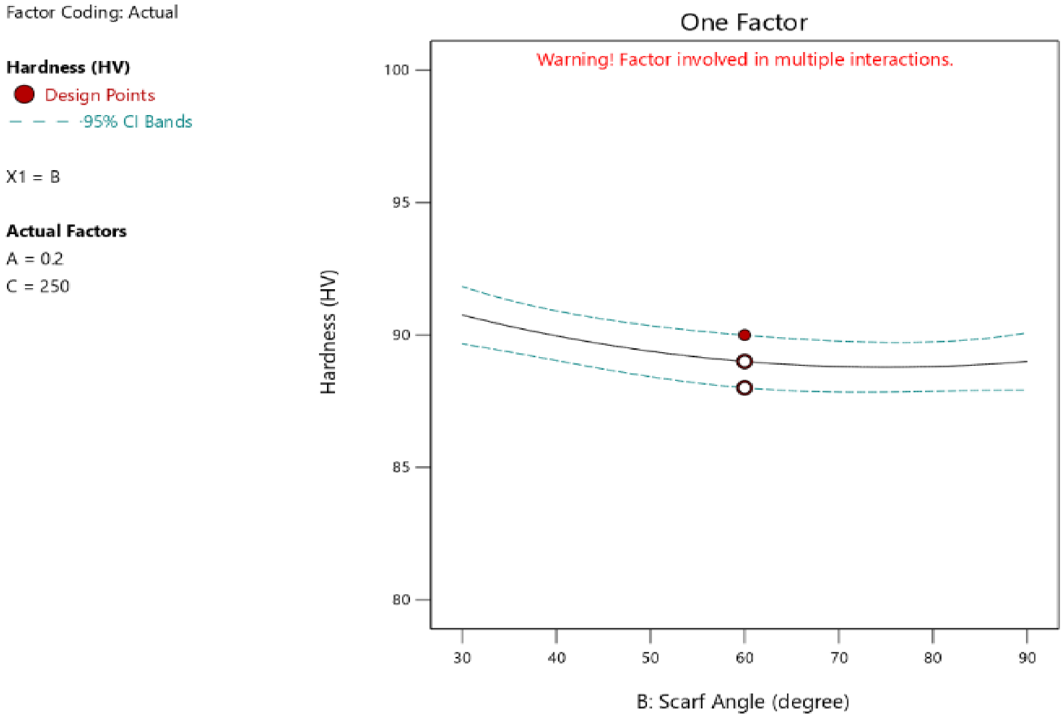


Figure 4: Effect of clearance gap, soaking temperature and scarf angle on hardness

3.5 Multi objective optimization

The process variables that affects the value of responses are clearance gap, scarf angle and soaking temperature. An optimization was carried out for finding maximum tensile strength, minimum hardness and minimum filler metal consumption. Goals apply to the factors and responses that were used for optimization are shown in table 11.

Table 11: Constraints values for the optimization for maximum tensile strength and minimum hardness

Name	Goal	Lower Limit	Upper Limit	Importance
A:Clearance Gap	is in range	0.1	0.3	3
B:Scarf Angle	is in range	30	90	3
C:Soaking Temperature	is in range	200	300	3
Tensile Strength	maximize	103.442	121.543	3
Hardness	minimize	81	96	3

Results of optimization shows in **table 12.** Parameters that provides maximum tensile strength, minimum hardness and minimum filler material consumption are Clearance gap 0.216 mm, scarf angle 63.79° and soaking temperature 294.35°C.

Table 12: Optimum conditions for maximum tensile strength and minimum hardness

Clearance Gap	Scarf Angle	Soaking Temperature	Tensile Strength	Hardness	Desirability
0.216	63.797	294.349	117.798	86.013	0.750

IV. CONCLUSION

1) Clearance gap, scarf angle and soaking temperature have a significant effect on tensile strength, Hardness of joint and filler material consumption. Among Clearance gap, Scarf angle and Soaking temperature, the effect of scarf angle and clearance gap are more dominant.
2) Ultimate tensile strength of the joint w.r.t. clearance gap, when increase then UTS increase, attain maximum value and then again start decreasing. Effect of scarf angle is also same as clearance gap on UTS. The effect of soaking temperature is not as much dominant as other two parameters.
3) Hardness of joint is decrease with increase in Clearance gap. The effect of scarf angle and soaking temperature on hardness of brazed joint are very less dominant.
4) For optimum joint design, Parameters that provides maximum tensile strength, minimum hardness and minimum filler material consumption are Clearance gap 0.216 mm, scarf angle 63.79° and soaking temperature 294.35°C.

V. FUTURE SCOPE

1) Effect of soaking time on the mechanical and metallurgical properties of the joint can be checked.
2) Comparative study of effect of different brazing techniques on output parameters can be recorded.
3) Microstructure and Non-destructive testing (Liquid penetrant testing) of joint can be studied.

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