March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

Effects of Spot Welding Parameters on the Shear Characteristics of Aluminum Honeycomb Core Sandwich Panels in Aircraft structure

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Abstract

Honeycomb structures possess the geometry of a honeycomb to permit the minimization of the quantity of the utilized material to reach minimal weight and minimal material cost. Today honeycomb cores are manufactured via the adhesive process from metal (usually aluminum). In this work, a resistance spot welding (RSW) was used as a new technique for manufacturing of honeycomb structure instead of an adhesivetechnique for aluminum alloys. The effect of resistance spot welding parameters on the shear force of spot welding for honeycomb structure was studiedvia employing theDesign of Experiment (DOE) software with the technique of Response Surface Methodology (RSM). The welding parameters were electrodes forces, welding time and squeeze time after welding. The experiments included welding (20) pieces from aluminum alloy 3003 with dimension (76×16)mm and 0.5mm as thickness according to American Welding Society (AWS).RSM technique was employed to model and optimize the shear stresses in terms of the welding parameters. Results showed that RSW shear strength at the optimum condition is 62.07MPa, while the shear strength of threetypes of adhesive materialis (0.128,0.371 and 1.28 MPa).That means the resistance spot welding is a suitable technique for manufacturing of honeycomb structure.

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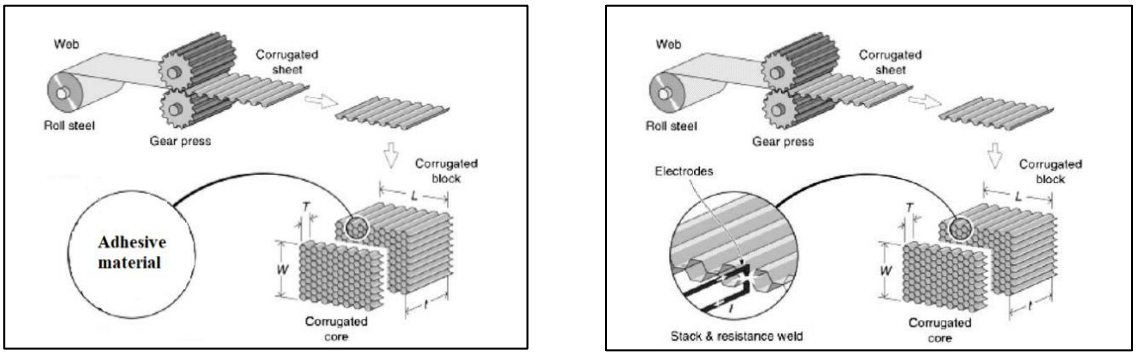
1-Introduction

Sandwich structures have extensive applications as lightweight composite materials in aerospace and shipbuilding due to their high capacity of stiffness, strength and energy absorption [1]. Sandwich panel consists from relative thin but stiff faces and thick but soft core,as shown in figure (1). There are many types of core like circle, rectangle and hexagonal (honeycomb structure) [2-8]. Nowadays honeycomb cores are widely used in the manufactured of sandwich structures composite because it provides a material with minimal density and relative high out-of-plane compression properties and out-of-plane shear properties [9].Al

March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

alloy 3003 has been selected to the manufacturing of honeycomb core structure, Al alloy was cut to multiple thin strips. The adhesion technique considered a common joint process that used for honeycomb joining which based on surface adhesion between two materials parts by using polymeric adhesive materials[10],[11]. During the adhesion joint, Al alloys may require some level of surface preparation to remove any unwanted chemical from the surface. Since aluminum forms a protecting layer, so it is inert to many chemical adhesions. This layer forms an insulated surface from adhesion of adhesive with aluminum if this layer breaks up due to interfacial locking or any surface preparation treatment will undergo of galvanic corrosion that will make the surface layer eat itself literally.

The presence of the adhesive bonding material in the honeycomb structure (i.e. Epoxy steel pro, 2k cyanoacrylate, super-fast glue wurth, and etc.) caused a weakness in the bonding region which is considered as a defect region and a reason for failure.However; most aluminum alloys can be joined by welding together. The electrical resistance spot welding (RSW) is suitable for joint of the Al alloy strips together to form a honeycomb structure. Three regions are recognized in a spot weld: a weld nugget with a cylindrical profile, a heat-affected zone (HAZ) and the base material sheets. These regions have different material properties. For example, the yield stress in the nugget is up to three time's upper than in the base material, and the plastic properties of the HAZ are non-homogeneous [12].



(a) Adhesive joint (b)welding joint

Figure 1. Honeycomb assemble [1]

Resistance spot welding is a welding process wherein coalescence is formed by the heat acquired from resistance to the electric current flows during the work portions held together below pressure from electrodes. The control function of the welding machine defines the welding cycle. The particular steps controlled are a squeeze, welding, and hold Time[13].

The domestic heating generated at the weld zone is due to the flow of the RSW machine current through the resistance of the welded materials. The pressure through the electrode tips, in which the current is flowing, carries the exerted portions to be welded at close connection before, during and after the current cycle welding. The requisite magnitude of the current time is selected depending on the material thickness and type the quantity of flow current and the area of the cross-sectional for the contact surfaces of the welding tip[14].

The presentresearch work aims to study experimentally the effect of welding parameters (time of welding, squeeze force as well as squeeze time after welding) on the shear strength of honeycomb structure made from aluminum alloy AA3003. After that, the RSM technique will be employed by DOE software to develop an empirical mathematical model for the shearstrength ofthe welded joint made by the RSW process within the used levels of welding parameters.

2ExperimentalWork

To develop the shear strength of honeycomb structure, two techniques joint are used welding joint and adhesion joint (common joint process) as illustrated in below.

Table 1,while themechanical properties of them are shown in **Table 2**to ensure that the used and standard alloys are in conformity and for the purpose of comparison [15].

2-1-2 welding machine

Resistance spot welding machine type (DN-100E) with single-phase was

2.1 Welding joint

2-1-1 Utilized material

The base material utilized in the current research work was aluminum alloy (AA3003) sheet with a thickness of 0.5 mm, which is used for manufacturing the automotive and aircraft structures. Chemical composition of used and nominal **(AA3003**) are listed in the **2-1-2 welding** machine

Resistance spot welding machine type (DN-100E) with single-phase was used in this work. To study the influence of welding parameters on shear strength of honeycomb structure, this machine has been modified as electrodes shape, welding time, squeeze force and squeeze time after welding. Figure 2 shows the resistance spot welding machine.

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Table 1: Chemical compositions of the used and standard AA3003

Element (wt%)	Mn	Fe	Si	Cu	Zn	Al
Used	1.14	0.5	0.135	0.126	0.008	Bal.
Standard	1-1.5	0.7 max	0.6 max	0.05-0.2	0.2 max	Bal.

Table 2: Mechanical properties of the used and standard AA3003[15]

Material	Ultimate Strength (MPa)	Yield strength (MPa)
Used	126	119
Standard	131	124

March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

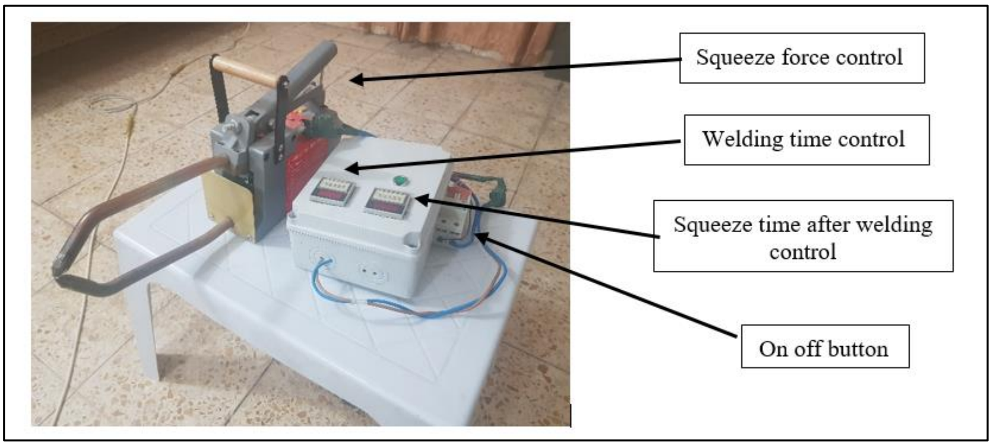

Figure2.Resistance spot welding machine.

2-1-3 Conditions of RSW

For investigating the effect of the welding on the shear strength of honeycomb structure induced via RSW process, three input parameters (welding time, squeeze force, and squeeze time after welding) were utilized as individualparameters within two levels (see **Table 3**). The selection of these levels was based on the previous practical expert and the data of experiments after using the welding machine.

Table 3:Levels of the used input parameters in RSW

Input factor	Units	Low level (-1)	High level(+1)
Welding time	sec.	2	4
Squeeze force	N	120	140
Squeeze time after welding	sec.	4	6

2-1-4 Procedure forwelding

The sheet was initially cut to sixty pieces with the dimensions of (76 x 16 x 0.5 mm). The dimensions of specimens were selected, depending on the AWS standardinaccordance with the American Welding Society (AWS)[16], as shown in figure 3, and after that,allsurfaces of specimens were cleaned for removingany contamination and oxides layers before welding. All experiments were carried outdepending on the DOE design matrix of the DOE software (see **Table 4**)forthe input welding parameters in two levels of input parameters to obtain their effect on the developed shear strength in RSW. The welded specimensfrom the AA3003sheets with the welding input factors are listed in figure 4according to**Table 4**.

Table 4: Design matrix of input factors and the measured response

Standard No.	Welding time (sec)	Squeeze force (N)	Squeeze time after welding(sec)	Av.Shear force(N)
1	2	100	4	168.0

TEST Engineering & Management
March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

2	4	100	4	92.0
3	2	140	4	110.0
4	4	140	4	95.0
5	2	100	6	138.0
6	4	100	6	95.0
7	2	140	6	88.0
8	4	140	6	50.0
9	1	120	5	50.0
10	5	120	5	35.0
11	3	80	5	170.0
12	3	160	5	70.0
13	3	120	3	72.0
14	3	120	7	85.0
15	3	120	5	200.0
16	3	120	5	208.0
17	3	120	5	218.0
18	3	120	5	206.0
19	3	120	5	190.0

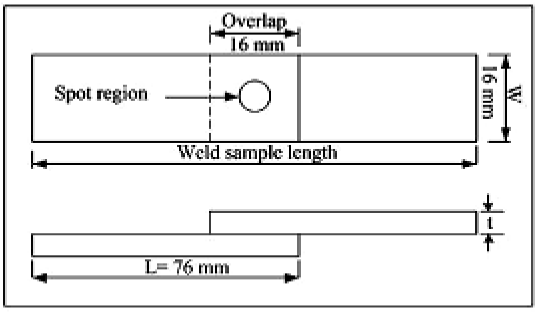

Figure 3: Overlapping of two welded plate [16].

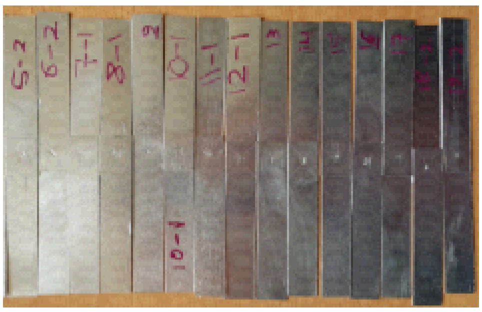

Figure 4. The welded specimens

March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

2-2 Adhesion joint

For comparison with the adopted welding in this study, Epoxy steel pro, 2k cyanoacrylate,and super-fast glue wurth were used in this work to adherethe aluminum strips that cutpreviously section [17]. Figure 5 shows adhered specimens

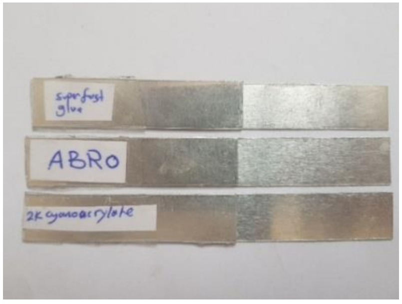

Figure 5: Aluminum strips adhesive using Epoxy steel pro, 2k

Cyanoacrylate and super-fast glue wurth

2.3 Measurements of shear Stresses

The shear strength was performed on a rectangular specimen, 76mm in the length and 16 mm in width, as shown in the figure 3. All the welded specimens are shown in figures 4 and 5 have been tested. The tension-shear test was performed at crosshead speed of 10mm/min. The specimens were gripped as shown in figure 6 with shims if thickness equal to that of the specimen.

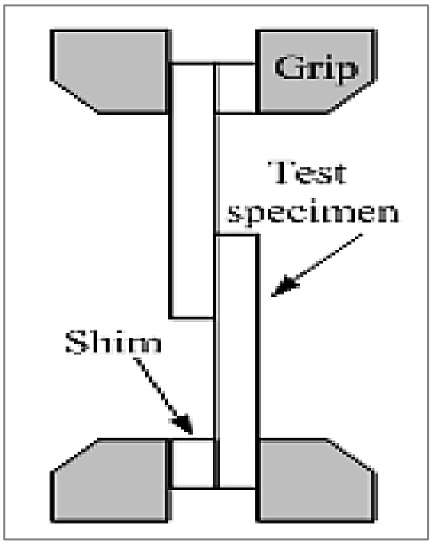

Figure 6:Schematic of a tensile strength test

2.4 Experimental Design

In this work, the RSM method was employedfor developing an empirical mathematical model dependingupon the data of experiments. A quadratic equation of the response surface should be regardedsince the curvature perhapsis not enough modeled via utilizing the first-order equationover the ranges of the normal workingcircumstances. 19 experiments were conducteddependingupon the experimental design matrix. Theseexperiments were randomly done according to the experiment order mentioned in **Table4**. Variouscoded levels between(-2)and(+2) were utilizedfor every factor, where eachused level is adapted to the actual value relevant to the coded one. Therefore, the studied input parametersin the RSW process are the welding time, the squeeze force as well as the squeeze time after welding. The experimental design matrix utilized for the input factors with the resultedaverage values of shear forcesis given in **Table4**. The predicted model within a (95%) confidence level was establishedby employing (Design-Expertversion 10) software.

3. Results and Discussion

3.1 Welding joint

3-1-1 Residual stress model

The proper model was chosen and established using the technique of (RSM), and the characteristics of the response characteristics were utilizedfor obtaining the model's regression equation. The values of experiments in **Table4** were employedfor developing the regression equation thatwas plotted for exploring the effect of the operation upon the variouscharacteristics of the response. A statistical analysis by ANOVA(analysis of variance) for the response surface quadratic model (shear force) was achieved to analyze the results to check the

March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

adequacy of this model (**Table 5**). In this table, the Prob> F valuesthat are less than (0.05)indicate that the terms of this model (A, B, A^2, B^2,and C^2) are significant. Accordingly, such model explains that the time of welding (A) and force of squeezing (B)possess the largest effect, whereas the time of squeezing (C) beyond welding possessesa little influenceupon the shear force. The developed empirical quadraticmodel forpredicting the shear force in the RSW process of AA3003 alloy is given as follows:

$$\begin{aligned} \text{Av. Shear Force} &= -1556.33446 + 233.55743 \\ &* \text{welding time} + 11.89949 \\ &* \text{squeeze force} + 316.05405 \\ &* \text{squeeze time after welding} \\ &- 41.03041 * \text{welding time}^2 - 0.054139 \\ &* \text{squeeze force}^2 - 32.03041 \\ &* \text{squeeze time after welding}^{\,2} \end{aligned} \quad (1)$$

The model adequacy checking was performed viathe residual analysis, and the outputs are depicted in the figures 7 and 8. Figure 7illustrates the normal probability plot. It is noted that the errors arespread normally as shown in suchfigure since the residuals present in a straight line. The standardized residuals related to the predicted values are revealed in figure (8). The residuals don't experience any explicit unusual style and are distributed in both positive and negative direction. That indicates the model is adequate. Figure 8elucidatesthat the predicted shear forcesvalues are close to the actual measured values in tests, explaining that the experimental values agree well with the predicted outputs.

The main effects plot shows that all the factors appearedto have an effect on the response variable (shear force). This method was used to study the effect of each welding parameter separately and its impact on the shear stress, it was obtained the following results, figure 9. The behavior of shear stress with the squeeze time after welding, squeeze force and welding time factors which indicated in the figure 9, showed that; the shear forces have direct proportion until the ultimate value at 5 sec, 120N and 3sec, respectively. And then these relationships become reversed

Table 5: ANOVA for the response surface quadratic model for shear force

Source	Sum ofsquares	f	Mean square	F value	p-valueProb > F
Model	63098.92		10516.49	0.81	< 0.0001 significant
A- Welding time, sec	2550.25		2550.25	.47	0.0181
B- Squeeze force, N	7656.25		7656.25	2.43	0.0005
C- Squeeze time after welding, sec	289.00		289.00	.85	0.3756
A^2	39865.14		39865.14	16.80	< 0.0001
B^2	11104.89		11104.89	2.54	< 0.0001
C^2	24294.42		24294.42	1.18	< 0.0001

TEST Engineering & Management
March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

Residual	4095.61	2	341.30		
Lack of Fit	3668.41		458.55	.29	0.0878 not significant
Pure Error	427.20		106.80		
Cor Total	67194.53	8			

Std. Dev.	18.47	R-Squared	0.9390
Mean	123.16	Adj R-Squared	0.9086
C.V.%	15.00	Pred R-Squared	0.7439
Press	17206.43	Adeq Precision	16.888

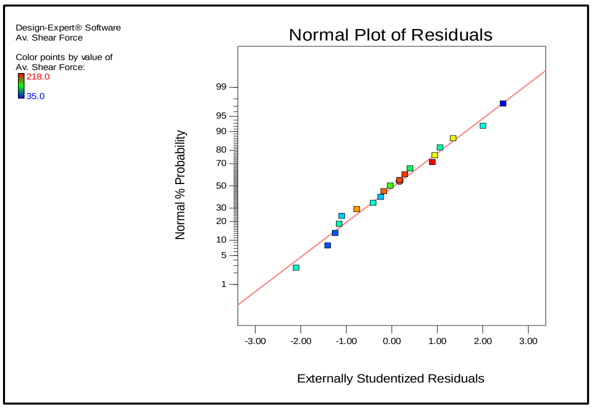

Fig. 7: Normal probability plot for shear force data

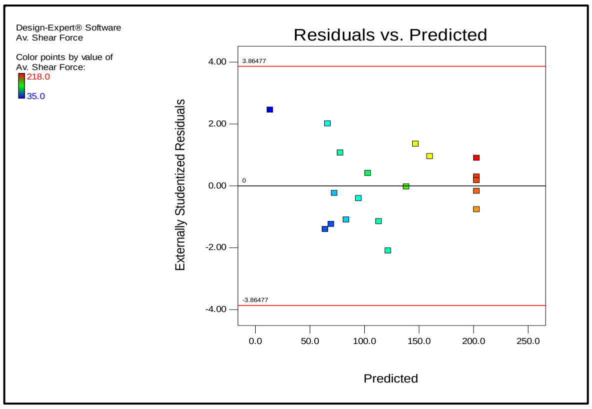

Fig. 8: Residual versus predicted responses for shearforce data

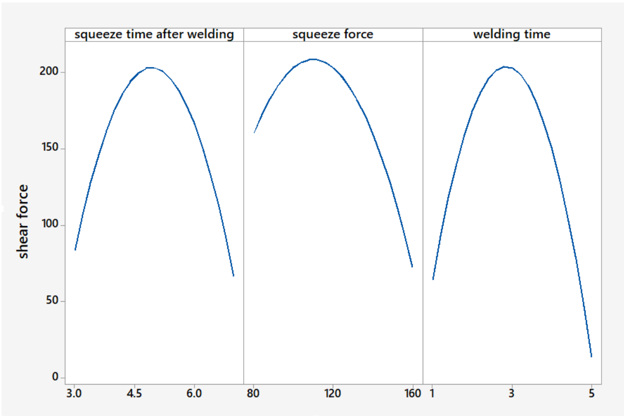

Fig. 9: Perturbation of shear stress showing the effect of each input parameter over the selected level.

Thisoutput is also corroborated by the (2D) contour plot and (3D) surface plot demonstrated in the figures 10 and 11, correspondingly in terms of squeeze force and welding time at the center level (medium value) of the squeeze time after the welding process for (5) seconds.

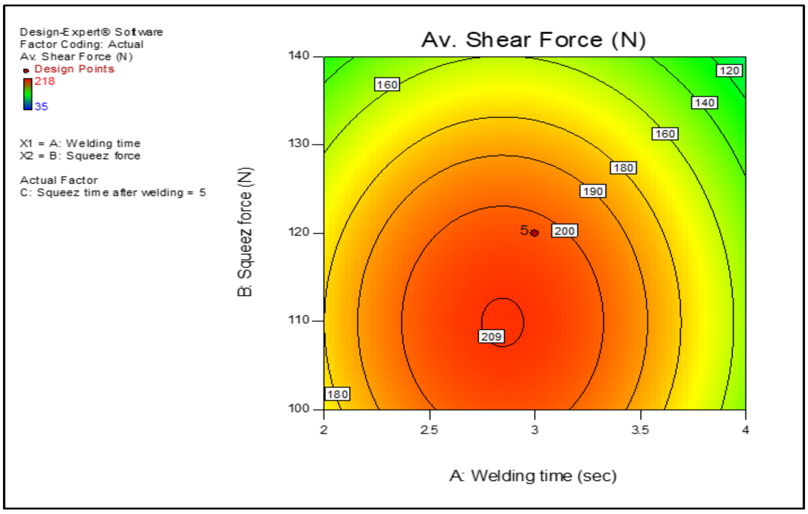

Fig.10: Contour graph of shear force as a function of welding timeandsqueeze force.

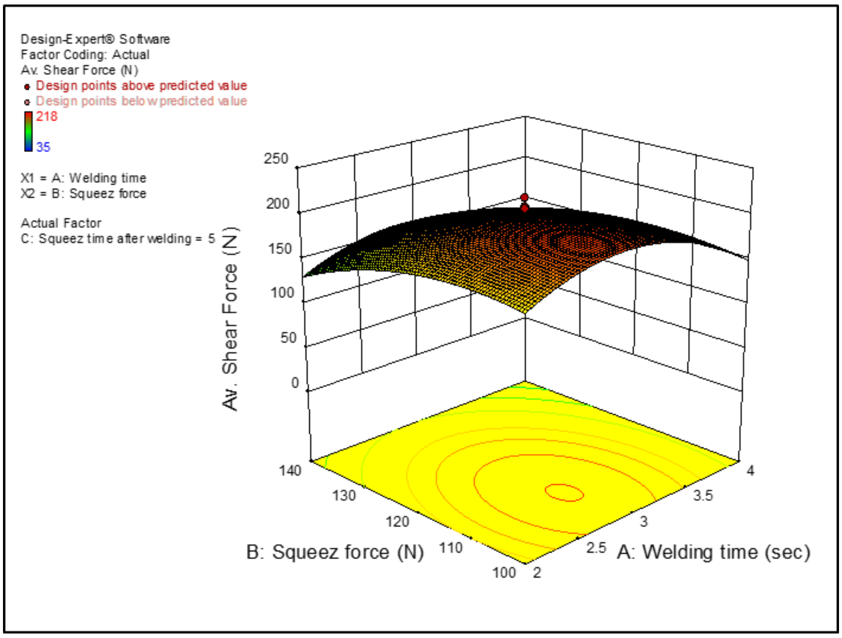

Fig.11: 3D Graph of shear force as a function of welding time and squeeze force

3-1-2 Shear force Optimization

The DOE software was employedfor performing the process of the numerical optimization and for determining the optimum combinations of the input factors to perform the needs as wanted. Accordingly, such software was utilized for the optimization aim dependingupon the prediction model results of the response(shear force) as a function of the input welding parameters: time, squeeze force, squeeze time after welding.

To build a new prediction model, which is an objective function named“Desirability” that admits for a proper combining the goals, was evaluated. This objective function (desirability) should be maximized viathe process of the numerical optimization, and it takes values from (0) to (1) for the goal. The goal characteristics may be varied by modifying the “Weight” or “Importance” of the objective function, and the optimization aimsto obtain the appropriategroup of statesfor satisfying the wholegoals. Commonly, these weights are used to establish the evaluation of the goal's(3D) importance via the maximization of the desirability of this investigation; weights weren't varied, because the shearforce (response) possesses the principal importance. The mainaim of this optimization process was to obtainthe maximum response that satisfies the variable characteristics with maximum desirability. The constraints of each input factorto optimizethe shearforce are given in **Table6**. Depending uponsuch table, one possible experimentsatisfied the usedconstraintsto determine the maximum value for shear force (209.55 N), as shown in the **Table7**witha maximum chosen desirability (0.954) for such experiment.

Table 6: Constrains of each variable for the numerical optimization of shear force

Types of variables	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weigh t	Importanc e
Welding time, sec	is in range	2	4	1		3
Squeeze force, N	is in range	100	140	1		3
Squeeze time after welding, sec	is in range	4	6	1		3
Av. Shear Force, N	maximize	35	218			3

Table 7: Optimal conditions used to obtain the maximum shear force.

Welding time, sec	Squeeze force, N	Squeeze time after welding, sec	Maximum Shear force, N	Desirability
3	110	5	209.555	0.954

3-1-3 Validation tests

For checking the resulted model validity, confirmation tests were conducted at the optimum predicted input welding parameters values found in sucha modelfor measuring the shear forces. The results of the measurements after the confirmation tests are listed with the predicted ones in the **Table 8** for a comparison aim, and such table illustrates that the experimental results agree well with the predicted and theresulted maximum error is 7%.

Table 8:The experimental and predicted values of the shear force

Welding time, Sec	Squeez e force,N	Squeeze time after welding, sec	Predict Maximum Shear force, N	Experiential Maximum Shear force, N	Max.Error %
3	110	5	209.555	195	7

3-2 Adhesion joint

The experiential result shear stress of adhesion specimens can be summarized in**Table 9**

Table 9: The experimental shear stress of adhesion specimens

March - April 2020
ISSN: 0193-4120 Page No. 7244 - 7255

Adhesive type	Shear stress (MPa)
Epoxy steel pro	95
2k cyanoacrylate	312
super-fast glue wurth	33

3-3 Comparison results

Table 10 shows the comparison results for adhesion joint and welding joint. It illustrated that the welding joints the best from adhesion joint

Table 10: the comparison results for adhesion joint and welding joint.

Joint type	Adhesive type	Shear stress (MPa)
Adhesion joint	Epoxy steel pro	0.371
	2k cyanoacrylate	1.218
	super-fast glue wurth	0.128
Welding joint	Optimum condition	62.07

4.Conclusions

From the results, the following points are concluded:

1- Depending upon the results ofthe DOE and RSM, the resulted optimum value for the maximum shear stress was obtained at (3 sec) welding time, (120N) squeeze force and (5 sec) squeeze time after welding. Where the optimum shear stress value was found (62.07 MPa).
2- A good agreement was found between the experimental results and the predicted ones of the shear force with a (7%) maximum error.
3- The DOE with the RSM was provedto be anadequate tool for predicting the shear stress for the wholevalues of the given input welding parameters utilized in the RSW operation.
4- In the comparison of the results between adhesion joint and welding joint, it is was found that the shear strength of welding is greater than the shear strength of adhesion by (60 MPa). So,resistance spot welding is a very suitable way to make a honeycomb structure.

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