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Experimental Analysis of Effects of Ultrasonic Welding on Weld Strength of Polypropylene Composite Samples

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ABSTRACT

In the present study, the ultrasonic welding process of plastics is used for overlap joining of polypropylene composites reinforced with glass fiber. The effect of three process parameters such as welding time, air pressure, vibration amplitude and the amount of glass fiber in the composite on tensile- shear strength of weld joints is investigated. To reduce the number of tests and cost, the response surface methodology of design of experiments is employed by considering the above four parameters at three levels. These parameters are also optimized to obtain maximum weld tensile-shear strength. The results showed that a maximum failure force of about 2.30 KN is obtained when air pressure, vibration amplitude, welding time and amount of glass fiber are 1.5bar, 32 microns, 0.4 seconds and 10 percent, respectively.

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1. INTRODUCTION

In recent years, thermoplastic composites have found many applications due to their diverse properties. Short processing time, improved fracture toughness and resistance to microcracks are some of the advantages of thermoplastic composites [1-4]. Among thermoplastic composites, polypropylene (PP) composites reinforced with glass fiber (GF) have drawn the attention of researchers [5-8]. Although glass fibers have less elastic modulus compared with carbon fibers and their fatigue resistance and adhesion are also comparatively weak, but they have high tensile strength and chemical resistance and due to their low price and suitable mechanical properties, they have many applications [9, 10]. Due to the widespread application of these composites, the necessity of using welding methods to join them is evident. Thermoplastic welding methods are divided into friction welding, thermal welding and electromagnetic welding based on producing heat at the joint area. On this basis, ultrasonic welding (USW) process is a type of friction welding [11]. It is a process which uses high frequency mechanical vibration to weld pieces together. The welding pieces are put beside each other under pressure and high-frequency mechanical vibration is applied based on joint geometry to transfer vibration through materials. Heat is generated through a combination of surface and inter-molecular friction [12]. X.Y.Dai et al. [13] examined the mechanical properties (tensile strength) of joints in PP composites reinforced with GF of short and long length based on vibration welding. Payeganeh et al. [14] examined tensile strength and appearance of joints made in butt welding of PP composites using friction stir welding (FSW). Ahmadi et al. [15] experimentally investigated the tensile-shear strength and appearance of overlap joints in PP composites reinforced with GF and carbon fibers welded by FSW method. Ultrasonic welding of metals, plastics and dissimilar materials is also reported by some researchers [16-21]. To join different plastics, USW has been used in different studies too [22-25]. Response surface method (RSM) is a technique of statistical analysis which is used in many fields to define the reasons of changes in response and association between response and input variables [26-

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28]. In this method, a set of experiments is designed to measure distinctive response. Based on this method, a mathematical model is developed to define the association between response and input variables.

This method can be used to predict linear, quadratic and interactive effects of input parameters on the response. The response can be maximized or minimized by selecting proper values of the input variable [29-32]. In this work, Box-Behnken technique and RSM is used to develop an estimation model to predict the effect of amount of GF and parameters of USW such as air pressure, time and vibration amplitude of horn on joint strength of overlap welds in PP/GF composite samples with thickness of 4 mm and 10, 20 and 30 Wt.% of GF. The above parameters are also optimized to obtain maximum tensile-shear strength.

2. MATERIALS AND METHODS

2. 1. Experimental Design In the present study, an experiment is designed by considering four factors as controlled input variables at three levels based on Box-Behnken method with two repetitions. The design and analysis of collected data is done through Minitab Statistical Software.

A few preliminary tests were done to determine the limits of process parameters. The criteria of choosing the practical limits of parameters were based on achieving good penetration welds without overheating.

2. 2. Methodology In the present study, PP composite sheets of 200mm*200mm*4mm dimension with different amounts of GF were prepared from extruded granules (PP+GF) by a hot press and no coupling agent was used. Three types of sheets made of Forolen PP1045GB, PP2045GB, PP3045GB (KIMIA FOROOZ Co., Iran) were used. Table 1 shows the mechanical properties of the sheets.

Ultrasonic welding machine (Maxwhit-Taiwan) with maximum 2000 watt power and 15 KHz frequency is used to make the overlap welds. A horn of aluminum alloy with square cross section of 24mm*24mm with rounded corners was used. The edge of one of the pieces was knurled such that the knurls could be used as energy director. After designing the experiment, a fixture was employed to do the overlap welding according to Table 2. Twenty seven test runs were repeated for two times and in an unordered manner as shown in Table 2 to prevent systematic errors.

2. 3. Tensile-shear Testing Method Dimensions of the samples were selected based on ASTM D5868 standard. Tensile-shear test was done with a speed of 5 mm/min on a Zuker tensile testing machine. The tests were done to determine the failure force of welds and the collected data were used to model the failure force of weld joints. Values of obtained forces from the experiment are shown in Table 2

3. ANALYSIS OF RESULTS AND MODELING

3. 1. Analysis of Variance Minitab Software was used to find the best model that describes the response parameter in regression analysis. In factorial design technique, analysis of variance (ANOVA) is usually used to determine the significance of the model and its terms [33]. A model or terms of a model is regarded as significant the P value of which is less than 0.05. Table of ANOVA for weld strength (failure force) as affected by input variables is shown in Table 3. Linear effects of pressure, time, amplitude, and amount of GF (%) as well as square effects of amplitude (amplitude* amplitude) and amount of GF (%GF*%GF) are important. All effects of interactions except interaction of pressure and GF amount (pressure*%GF) are effective too. In addition, Table 3 shows that the value of R^2(Predicted)=79.13% is close to the value of R^2(Adjusted)=86.28% . Value of R^2 is equal to 89.71% which is close to 100 and this shows the adequacy of this model.

The final mathematical model of response is used to predict the failure force of the weld in the design space which is provided based on uncoded factors as in Equation (1).

$$\begin{aligned} F_{max} = & -15021-2404A+1103.5B+5332.8C \\ & +152.4D-16.7B^2-2.7D^2+66.7AB \\ & +427.8AC-249BC-3.7BD+54.8CD \end{aligned} \tag{1}$$

In Equation (1), A is the pressure (bar), B is amplitude (micron), C is time (second) and D is the percentage of GF. Putting the value of these parameters in this equation can contribute to estimation of failure force (F_{max}).

Normal probability of residuals and chart of residuals are shown in Figures 1 and 2 based on estimated response. Other tools are used to examine the adequacy of the model. Due to the fact that points on the chart of normal residuals have no significant deviation from straight line, one can conclude that this model has sufficient adequacy [34, 35]. The points in Figure 2 show no apparent pattern and abnormal structure.

3. 2. Validation of Developed Model Validity of the developed model was verified by doing 5 extra tests. These tests were done by using random values of the input parameters within the limits of process parameters for which a model had been suggested. The actual results which are the mean of three repetitions of each test and estimated values and percentage of error between actual values and estimated values of the answer are detailed in Table 4. Low values of error percentage between actual values and estimated one show that suggested model can predict the results with sufficient estimation.

3. 3. Effect of Process Parameters on Response

Figure 3 shows the effect of main parameters of the process on weld failure force. This figure shows the effect of each parameter on strength (weld failure force) without considering the condition of other parameters. As it is evident, increase of amplitude and time of welding has a negative effect on strength. This effect is due to the fact that increase of time and amplitude causes increase of defects resulted by more heat at the joint. These defects are made due to flow of material in weld seam and adhesion of the material to the surface of fixture and reduction of cross-section of the weld. With an increase in pressure, the effect of horn cross-section on the samples at the location of horns becomes deeper and this effect leads to concentration of stress in this area and deformation increases too. On the other hand, increase of pressure leads to increase of penetration.

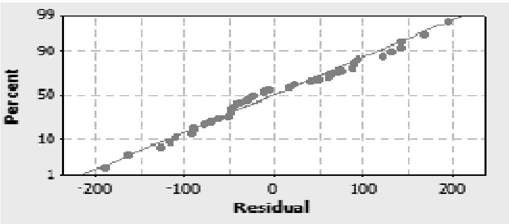


Figure 1. Probability of normal residuals

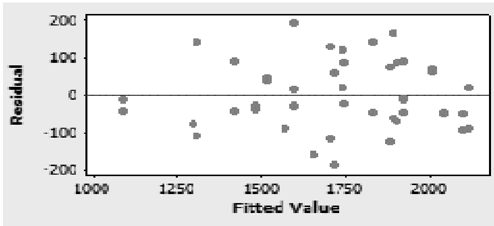


Figure 2. Residuals based on estimated values

TABLE 1. Mechanical properties of GF/PP sheets based on ASTM/D836

Type of Material	Elastic Modulus (MPa)	Tensile Stress at Break (MPa)	Elongation at Break (%)
Composite of 30% GF	3451	25.3	13.2
Composite of 20% GF	4729	43.9	15.9
Composite of 10% GF	2707	32.8	16.3

TABLE 2. Tests runs and the obtained responses

Test	Factors				Response			
	Pressure (bar)	Range of Amplitude(μM)	Time (S)	Amount of GF (%)	First Force (N)	Failure	Second Force	Failure
1	1.5	27	0.8	20	2079		2070.9	
2	2.5	27	0.8	20	1836		1724	
3	1.5	33	0.8	20	1793.8		1616.4	
4	2.5	33	0.8	20	1741.2		1860.2	
5	2	30	0.4	10	1471.1		1101.5	
6	2	30	1.2	10	1792		1477	
7	2	30	0.4	30	1450.8		1197.7	
8	2	30	1.2	30	1568.2		1566.9	
9	1.5	30	0.8	10	1829.5		2059.2	
10	2.5	30	0.8	10	1783.9		1972.1	
11	1.5	30	0.8	30	1456.6		1443.7	
12	2.5	30	0.8	30	1514.9		1378.1	
13	7	27	0.4	20	2014		1409.9	
14	7	33	0.4	20	1991		1995	
15	7	27	1.2	20	2008.8		2051.8	
16	7	33	1.2	20	1837.2		1217.1	
17	1.5	30	0.4	20	2023.6		2137.3	
18	2.5	30	0.4	20	1975.6		1755.8	
19	1.5	30	1.2	20	1605.7		1017.8	
20	2.5	30	1.2	20	1991.4		1833.7	
21	2	27	0.8	10	1588.8		1836.9	
22	2	33	0.8	10	1527.3		1777.7	
23	2	27	0.8	30	1564.7		1556.5	
24	2	33	0.8	30	1076		1045.1	
25	2	30	0.8	20	1917.3		1598	
26	2	30	0.8	20	1874.8		2241.2	
27	2	30	0.8	20	1911.2		2013.7	

TABLE 3. Analysis of variance (after removing ineffective terms)

Source	Sum of squares	df	Mean square	F-value	P value prob.	Significance
Regression	3128294	11	284390	26.16	0.000	
Linear	1124265	4	169177	15.56	0.000	
Pressure	15656	1	109078	10.04	0.003	
amplitude	209616	1	250447	23.04	0.000	
Time	29410	1	208173	19.15	0.000	
%GF	869583	1	148869	13.70	0.001	
Square	1097543	2	392997	36.16	0.000	
Amplitude * Amplitude	51514	1	227734	20.95	0.000	
%GF*%GF	1046029	1	693607	63.81	0.000	
Interaction	906487	5	181297	16.68	0.000	
Pressure*Amplitude	80120	1	80120	7.37	0.010	
Pressure*Time	19317	1	36915	3.40	0.074	
Amplitude*Time	506367	1	514768	47.36	0.000	
Amplitude*%GF	96657	1	96657	8.89	0.005	
Time*%GF	204025	1	204025	18.77	0.000	
Residual error	358692	33	10869			
Pure error	225614	22	10255			
Total	3486986	44		S = 104.257 PRESS = 727787		
				R-Sq = 89.71% R-Sq(pred) = 79.13%		
				R-SQ(ADJ) = 86.28%		

TABLE 4. Verification tests

Test	Pressure (bar)	Amplitude (µm)	Time (s)	GF(%)	Actual Force (N)	Estimated Force (N)	Error (%)
1	1.5	27	0.4	30	1255.62	1197.75	4.6
2	2.5	30	0.8	20	1941.75	1817.14	6.41
3	1.5	33	1.2	20	1112.63	1054.05	5.26
4	2	30	0.8	10	1901.49	1805.12	5.06
5	2.5	33	1.2	10	1294.84	1213.91	6.25

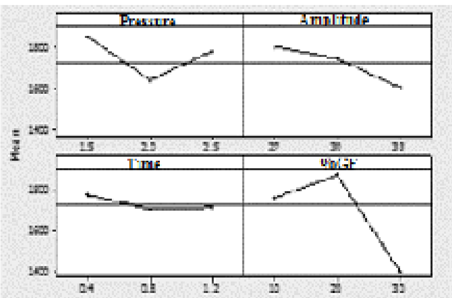
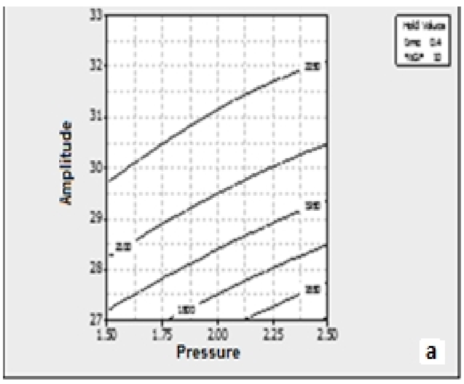


Figure 3. Effects of main parameters on weld failure force



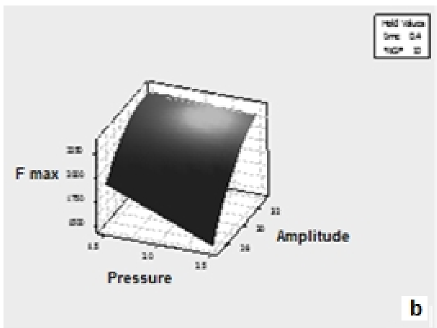
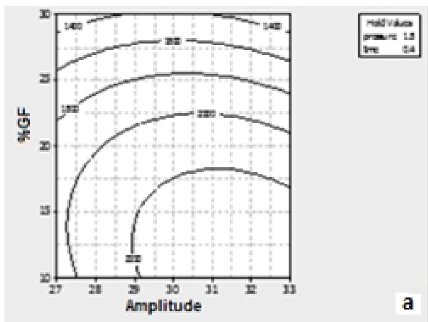


Figure 4a. Two-dimensional plot **4b.** surface response diagram the effect of pressure-amplitude on weld failure force with time=0.4s and GF=10%



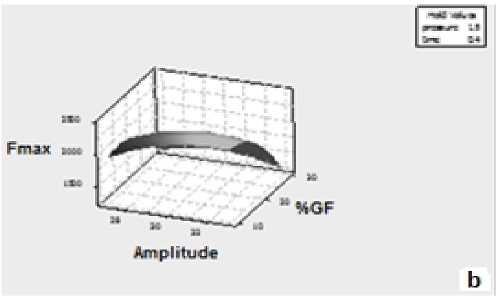


Figure 5a. Two-dimensional plot **5b** surface response diagram of GF% on weld failure force with time=0.4s and pressure=1.5 bar

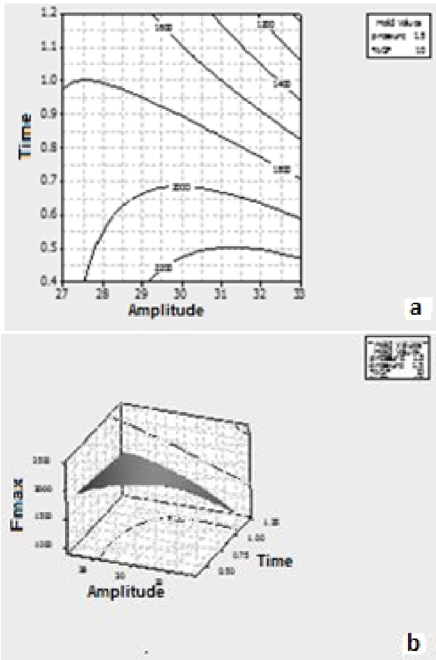


Figure 6a. Two-dimensional plot **6b** surface response of effects of time-amplitude on weld failure force with GF=10% and pressure=1.5 bar

In other words, increase of pressure is followed by an increase in concentration of stress and deformation at the joint as well as reduction of strength. This condition is observed by increase of pressure up to 2 bar, but more increase of pressure up to 2.5 bar has higher effect on strength. The reason for decline of strength at higher percentages of GF might be due to the less surface area available for penetration of PP and insufficient adhesion of GF to the matrix. Due to the effectiveness of interaction effects on response, the associated figure can't be used to optimize the response. Figures 4 to 6 show two and three dimensional plots of the effect of interactions on strength (failure force). Figures 4a and 4b show that decrease of pressure and increase of amplitude are followed by increase of weld failure force. At higher amplitudes, change of pressure hasn't significant effect on the strength and increasing simultaneously the pressure and amplitude causes the strength of weld remain constant. Selection of proper factor levels (pressure close to 1.5 bar and amplitude of 30-33 micron) can help one to obtain a high strength.

Figures 5a and 5b show the interaction effect of amplitude and %GF on strength. Increasing amplitude and decreasing the percentage of GF lead to increase of weld failure force. Combination of about 30-33 micron of amplitude and 10-17 % of GF yields maximum failure force. Figures 6a and 6b show that with maximum amplitude, increase of welding time leads to the reduction of weld failure force. In other words, maximum failure force occurs with welding time of 0.4 to 0.5 second and amplitude of 30-33 micron. Furthermore, simultaneous increase of the amplitude and welding time shows a negative effect on strength of the weld. In other words, with higher amplitudes, lower welding times should be used to obtain high weld strength. According to ANOVA (Table 3), it is found that the effect of time-amplitude interaction is the most significant, because its F-Value is more compared to other interactions. The interaction of pressure-time considering its F value has minimal effect on strength of the weld. As a result, more attention should be given to the changes in amplitude and welding time because the weld strength is severely affected by these parameters.

4. CONCLUSION

- A second-degree model was developed to estimate the weld failure force within an experimental design space.
- Amplitude, welding time, amount of GF and air pressure are the most significant factors affecting the weld tensile-shear strength.
- Increase of pressure up to 2 bar can decrease strength but beyond this value the strength increases.
- Increase of welding time and amplitude has a negative effect on strength.
- Increase in the amount of GF to more than 20 percent reduces the strength.
- Based on interaction effects, maximum strength can be obtained at 30-33 micron amplitude, 0.4 second welding time, 10 percent GF and 1.5 bar pressure.

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Weld Failure Force

چکیده

در تحقیق حاضراز فرایند جوشکاری فراصوتی پلاستیک ها برای اتصال لبه رویهم کامپوزیت پلی‌پروپیلن تقویت شده با الیاف شیشه استفاده شده است. اثر سه پارامتر فرایند از قبیل زمان جوشکاری، فشار هوا، دامنه ارتعاش و نیز مقدار الیاف شیشه موجود در کامپوزیت بر استحکام کششی برشی اتصالات جوش‌ها مورد بررسی قرار گرفت. به منظور کاهش تعداد آزمایشات و هزینه، روش سطح پاسخ جهت طراحی آزمایشات با در نظرگرفتن چهار پارامتر مذکور در سه سطح به کار گرفته شد. بهینه سازی پارامترها جهت بدست آوردن بیشترین میزان استحکام نیز انجام شد. نتایج تحقیق نشان داد که بیشترین نیروی گسیختگی حدود ***KN*** ۲/۳را می توان در فشار هوای ۱/۵بار، دامنه ارتعاش ۳۲ میکرون، زمان جوشکاری ۰/٤ ثانیه ومقدار الیاف شیشه ۱۰٪ به دست آورد.

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