Experimental and computational investigation of adhesive joints subjected to impact loads

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Abstract

In recent years, the strength of the adhesive joints under impact loading has become important because their use expands to the aircraft and automobile industries. The impact strength of adhesively bonded cylindrical components is affected by the various factors such as the type of adherent, surface roughness, adhesive thickness, and operating temperature. In this study, the effect of three surface roughness values on impact strength is experimentally investigated and the results are discussed. Results showed that optimum surface roughness values were found in the range R_a= 1.5 to 2.5 μm. The highest impact strength was obtained in stainless steel adherent while the lowest one was obtained in aluminium specimens. Materials with higher free surface energy had higher impact strength values. The effect of adhesive thickness on impact strength was dependent on the type of adherent. Additionally, an impact strength prediction model was developed using Artificial Neural Network (ANN). The impact strength prediction results showed that developed artificial neural network model was convenient and powerful tool for impact strength estimation of adhesively bonded joints.

Key words: impact load, adhesive joints, adhesive thickness, surface roughness, ANN

1. Introduction

Adhesive bonding has been often used to join various kinds of structural components. The adhesive joints in actual products may sometimes be subjected to impact loading. The most typical type of adhesive joint for structural adhesion is lap joint. Shear stress is prominent in the adhesive layer of lap joints. Therefore, the adhesive strength under the impact shear stress must be measured. Impact strength is one of the most important properties for a part designer to consider, and it is the most difficult to quantify.

A lot of procedures have been developed to evaluate the impact performance of adhesively bonded joints because of intensive interest in a wide variety of applications, and some of them have been adopted as a standard. The methods using a pendulum hammer, the so-called Charpy or Izod tests, are the most usual techniques for the impact test of relatively low impact velocity. A standard, ASTM Block Impact Test (ASTM D950-3) is a variation of such pendulum hammer methods modified to be suitable for the evaluation of adhesive joints, and it is the most common and trendy one [1].

Adams and Harris [2] calculated the stress distribution in the specimen of the block impact test using the Finite Element Method (FEM) in some cases of changing loading points. They concluded that the main information that could be derived from this test was a quantitative comparison of the ability of various adhesives to withstand high loading rates, and the transfer of results to a practical situation was suspect. In the experiments, strength assessment of adhesives was carried out using four different types of epoxy adhesives. The results indicated the importance of ductility for adhesives in order to withstand impact loading.

Studying the effect of thickness of the adhesive on the fracture behaviour in adhesive joints under Mode I loading, Chai [3] concluded that the fracture energy became stabilized at a bond thickness less than 0.03 mm, or greater than 0.5 mm, while the maximum fracture energy was observed at 0.22 mm. In another study [4], the aluminium alloy (6061-T6) plates were joined with epoxy adhesive. The static and fatigue

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strength of the joint was studied experimentally and with the finite elements method. In static experiments, adhesive thickness of 0.3 mm had higher failure forces than 0.1 mm thickness.

Bezemer et al. [5] tested specimens with three adhesives at five layer thicknesses and three test speeds. The results of the tests indicated that a tough adhesive had larger energy absorption at impact than a brittle adhesive. Depending on the adhesive used and the test speed, different optimum adhesive thicknesses were observed. Increasing adhesive thickness gives a better impact strength for tough adhesives only. Sawa et al. [6] investigated the stress wave propagation and stress distribution in single-lap adhesive joints subjected to impact tensile loads. Examining the effects of Young's modulus of the adherents, the overlap length, the adhesive thickness and the adherent thickness on the stress wave propagation and stress distribution at the interfaces, Sawa et al. found that the maximum stress occurred near the edge of the interface and that it increased with an increase of Young's modulus of the adherents.

Kihara et al. [7] designed a test to study the response of a thick adherent shear joint subjected to various impact stress waves and observed that the type of fracture was associated with the level of the incident stress. Higuchi et al. [8] conducted the dynamic analysis of butt joints of cylindrical steel rods subjected to tensile impact loads using the three-dimensional finite element method and showed stress variation in the adhesive layer with respect to time and the presence of stress singularity at the circumferential edge of the adhesive layer.

In an experimental study carried out for both static and dynamic loading conditions, Sekercioglu et al. [9] determined the effect of different surface roughness values on bonding strength. Results showed that optimum surface roughness values were found in the range from $R_a = 1.5$ to 2.0 µm. In another study [10], the effect of three different adherents (steel, bronze and aluminium) on bonding strength was experimentally investigated, and the highest joint strength was obtained in bronze adherent while the lowest value was obtained in aluminium adherent.

The type of material has a significant effect on the impact strength. Higher impact strength of adhesive joints was found for chromium based hardener for some joints such as steel-steel and aluminium-aluminium joints [11]. In a study [12] about the impact strength of epoxy and polyurethane resins filled with graphite, a decrease in impact strength with an increase in filler content was observed, and the highest values of impact strength were found for polyurethane/graphite composites.

Investigating the impact strength of epoxy and polyurethane resins filled with silver-coated inorganic particles and fibres, Novak et al. [13] found the decrease in impact strength with an increase in filler content. The highest values of impact strength were found for epoxy/silver-coated short fibre composites. The authors reported that the decrease of strength of adhesive joint to aluminium with an increase in filler content was observed while the highest strength of adhesive joints was found for the adhesives based on epoxy/silver-coated fibre composites.

As summarized above, the previous studies showed that the relationship between roughness, adherent material, adhesive thickness and impact strength was unclear. The object of the present study is to clarify the influence of the surface roughness, adherent material and adhesive thickness on the impact strength of adhesively bonded components. The effect of these three parameters on impact strength was experimentally and computationally investigated.

2. Test materials and experimental procedure

In this study, the tests were carried out according to the ASTM D950-03 standard [14] with a pendulum-type impact machine. CEAST P/N Izod impact test machine was used in the experiments. The test machine with manual brake had an apparatus for energy from 1 to 25 J (Fig. 1). This machine has been used to conduct resilience test on thermoplastic materials, in order to determine their impact fragility characteristics under standard stress conditions.

Steel, copper and aluminium materials were used in the experiments because these are very common materials in general machinery industry. Figure 2 shows the dimensions and geometry of specimens which were carried out according to the ASTM standard. The different surface roughness values for copper and aluminium were obtained using the abrasive sandpaper

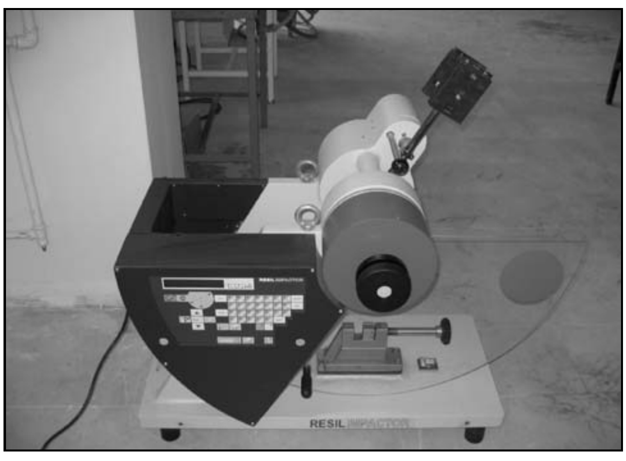

Fig. 1. Izod impact test machine.

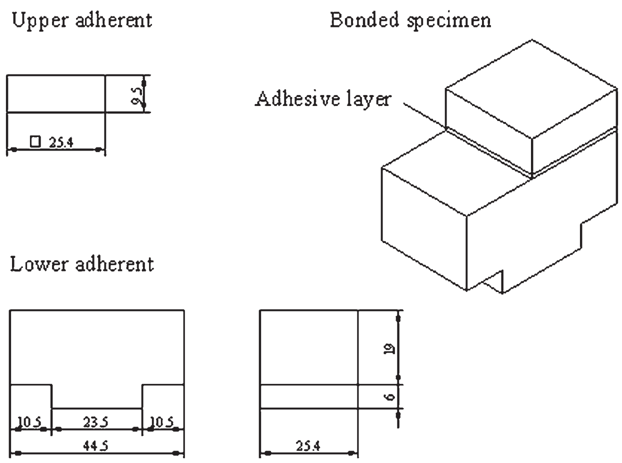

Fig. 2. Dimensions of test specimens according to ASTM 950-3 standard.

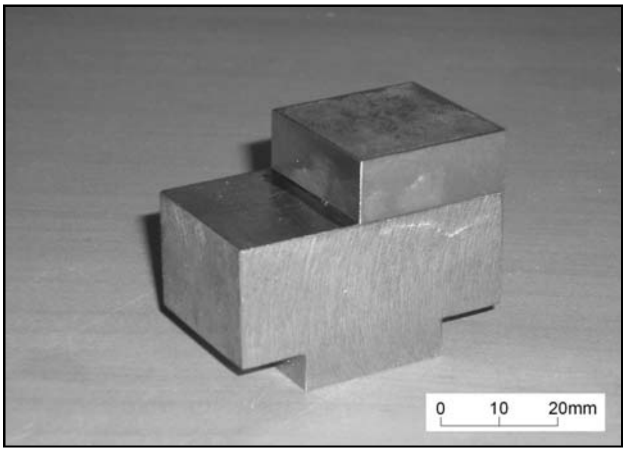

Fig. 3. Bonded test specimen.

with various mesh numbers (P220C, P600C, P800C). The steel specimens were soaked into hydrochloric acid (HCl) to prepare suitable surface roughness. The surface roughness of treated specimens was measured using a Mahr Perthometer M2 profilometer.

The specimens were cleaned with Loctite 7063, a type of general purpose cleaner for preparing surfaces to be bonded with adhesive. After the cleaning of machined specimens, Loctite Hysol 3421 adhesive was applied on the surface of each part. Loctite Hysol 3421 is a two component epoxy adhesive which cures slowly at room temperature after mixing. It is a general purpose, flowable adhesive which develops high strength and has excellent moisture resistance. The long working life and medium viscosity (40 Pa s) make this adhesive system suitable for large surfaces and where adjustment time is needed after assembly [15]. The adhesive thickness was obtained by using 0.5 mm long wires with three different outer diameters (0.1 mm, 0.3 mm, 0.5 mm). These wires were located at all corners of adherent surface. After that, these bonded specimens were left for curing process for 24 hours at room temperature (Fig. 3).

3. Impact strength prediction with ANN

Neural network modelling is an empirical modelling method in which a very flexible function is fitted to a set of data by adjusting the parameters of the network, also known as the weights. Basically, artificial neural networks are computer programs designed to develop and discover new information by using the learning function like a human brain. It is very hard or impossible to develop these skills with traditional programming methods. For this reason, it can be said that artificial neural network is a computer science division about adaptive information processing developed for occasions where the programming is very hard or impossible [16].

An attempt has been made to predict impact strength of adhesively bonded joints by using the data from experimental studies. In a first instance, half of the data sets were randomly selected from the database to serve as a test. None of these sets were used in training the present network. The remaining data were then divided in two sets, also randomly selected. The first one, containing 80 % of the lines, was used to train a number of models, while the second, containing the rest of the database, was used to validate the training and select an optimum committee of models. This procedure has been described numerous times in the literature. In the present study, a commercial package [17] was used which implements the algorithm written by Mackay [18].

4. Results and discussion

4.1. The effect of surface roughness

The effect of surface roughness on adhesive bonding strength was investigated for the different surface roughened specimens. Experimental conditions are given in Table 1. Experimental and predicted results are shown in Figs. 4, 5 and 6. The lowest joint strength was obtained in $R_a = 0.5$ μm surface roughness and the optimum value was obtained with $R_a = 1.5$ μm surface roughness. It was observed that as the roughness increased over the optimum range from $R_a = 1$ to 2 μm, the strength values decreased. The reason of minimum value for $R_a = 0.5$ μm might be the mechanical interlocking disappearance due to inadequate penetration of adhesive on smooth surfaces. When the surface roughness increases more than ne-

Table 1. Test conditions for determination of the effect of surface roughness

Adherent materials	Steel-Steel					Stainless Steel-Stainless Steel	Al-Al			Cu-Cu		
Width/length (mm)	25.4/25.4 = 1					25.4/25.4 = 1	25.4/25.4 = 1			25.4/25.4 = 1		
Adhesive thickness, s (mm)	0.1					0.1	0.1			0.1		
Number of specimen	25					5	15			15		
Surface roughness, R_a (μm)	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**1.5**	**0.5**	**1.5**	**2.5**	**0.5**	**1.5**	**2.5**
Average absorbed energy (J)	12.1	13.0	18.6	16.8	16.7	19.5	5.6	5.7	4.9	6.9	6.8	8.1
Average impact strength (kJ m^{-2})	18.73	19.97	28.91	26.04	25.91	30.20	8.80	8.94	7.63	10.80	11.90	11.01

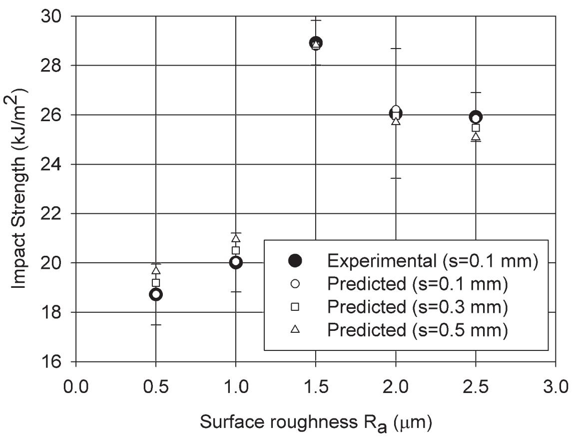

Fig. 4. Relationship between impact strength and surface roughness for steel material.

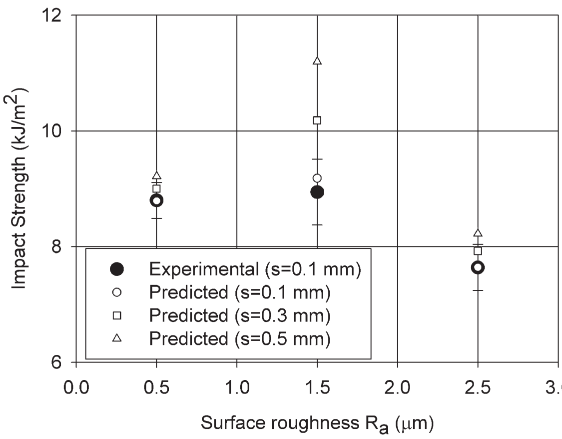

Fig. 5. Relationship between impact strength and surface roughness for aluminium material.

cessary, the strength values decrease. It can be said that the thickness of the adhesive increases partly and the adhesive cannot spread on the substrate surface because of too much roughness. Therefore, insufficient wetting occurs and then strength values decrease. In order to obtain the optimum wetting in the adhesive joints, the adherent surface roughness should be considered.

4.2. The effect of adherent type

The effect of four different adherents (steel, stainless steel, copper and aluminium) on bonding strength was investigated. The experimental conditions are given in Table 1. As it can be seen in Figs. 7, 8 and 9, when the different adherent was used, impact strength values of the joint changed considerably. The highest joint strength in stainless steel-stainless steel materials and the lowest joint strength in aluminium-aluminium materials were obtained. Normally, the failure phenomenon in adhesive joints is desired among adhesive molecules. The cohesive failure was observed on steel and stainless steel specimens while the adhesion failure was observed on aluminium specimens. Aluminium consists of weak bonding forces with adhesive because of passive materials. Bonding forces are affected by many chemical and physical phenomena. During the curing process, various chemical reactions occur between adherent and adhesive materials.

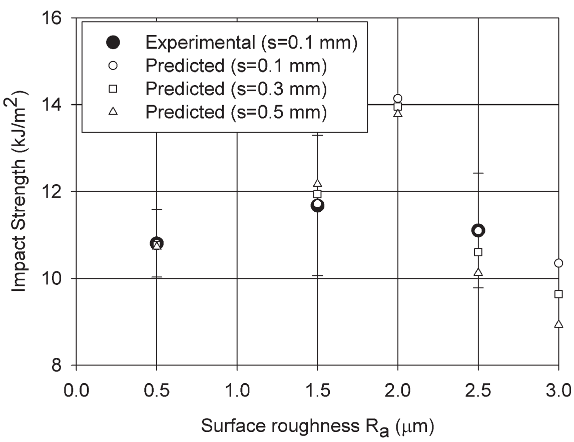

Fig. 6. Relationship between impact strength and surface roughness for copper material.

T a b l e 2. Test conditions for determination of the effect of adhesive thickness

Adherent materials	Al-Al			Cu-Cu		
Surface roughness, R_a (μm)	1.5			1.5		
Width/length (mm)	25.4/25.4			25.4/25.4		
Number of specimen	15			15		
Adhesive thickness, s (mm)	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
Average absorbed energy (J)	5.7	6.5	7.4	6.8	8.0	7.5
Average impact strength (kJ m^{-2})	8.94	10.13	11.50	11.90	12.45	11.68

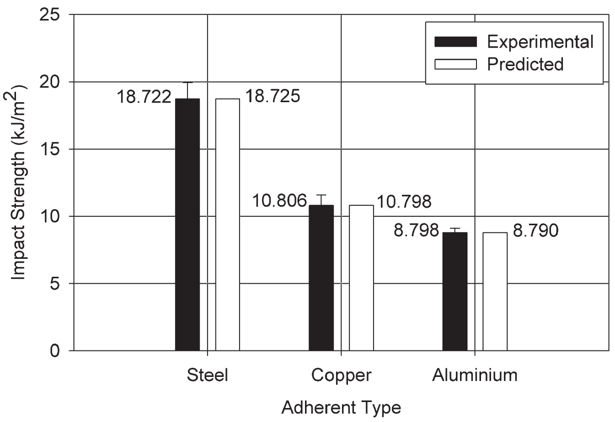

Fig. 7. Relationship between impact strength and adherent type for $R_a = 0.5$ μm.

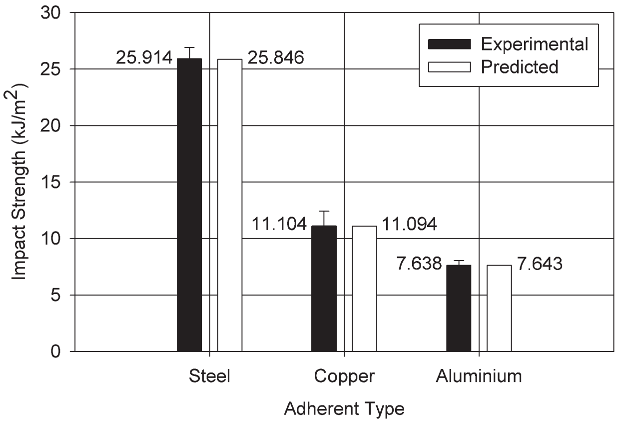

Fig. 9. Relationship between impact strength and adherent type for $R_a = 2.5$ μm.

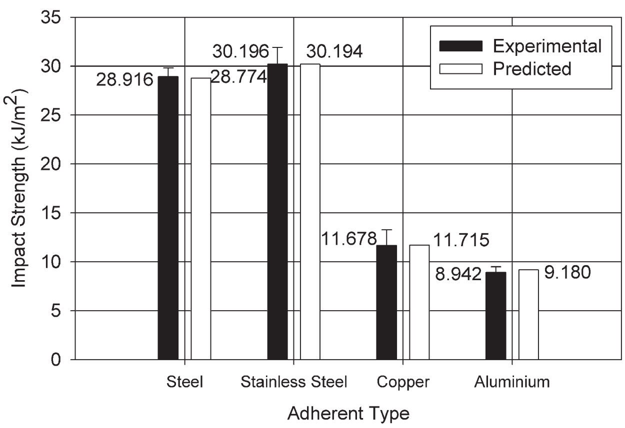

Fig. 8. Relationship between impact strength and adherent type for $R_a = 1.5$ μm.

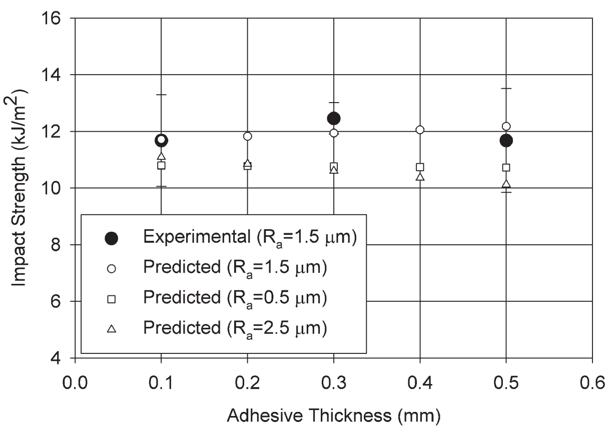

Fig. 10. Relationship between impact strength and adhesive thickness for copper material.

4.3. The effect of adhesive thickness

The effect of adhesive thickness on adhesive bonding strength was experimentally investigated. During the tests, the adhesive thickness was varied from 0.1 to 0.3 or to 0.5 mm, and the surface roughness was held constant. Experimental conditions are given in Table 2. Different results were obtained depending on the adherent type while the thickness of adhesive increased. Experimental and predicted results are shown in Figs. 10 and 11. It was observed that for aluminium materials, as the adhesive thickness increased, the impact strength also increased. Different results were obtained for copper materials since the maximum impact strength was at 0.3 mm adhesive thickness. These differences were most likely to be arisen from the interac-

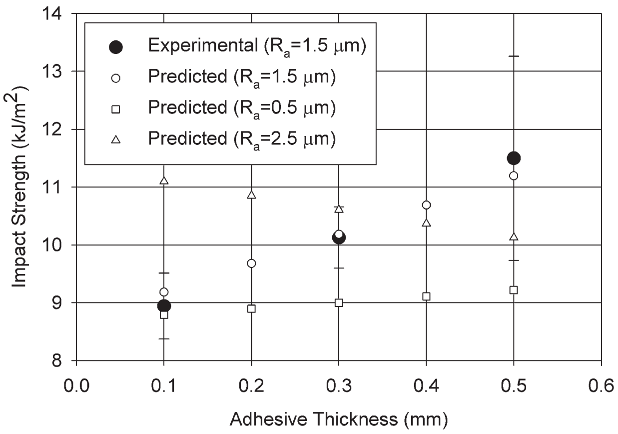

Fig. 11. Relationship between impact strength and adhesive thickness for aluminium material.

tion between adhesive and adherent during the curing process.

5. Conclusions

In this research, the tests were carried out according to the ASTM D950-03 standard with a pendulum-type impact machine. The effects of surface roughness, adherent materials and adhesive thickness on impact strength were investigated. From the experimental observations and ANN results, the following conclusions may be concluded:

1. The low impact strengths were obtained for both the very smooth surfaces ($R_\mathrm{a} < 1.0\,\mu\mathrm{m}$) and very rough surfaces ($R_\mathrm{a} > 2.5\,\mu\mathrm{m}$). For high impact strength, the optimum surface roughness was obtained in the range $R_\mathrm{a} = 1$ to $2\,\mu\mathrm{m}$. The surface roughness should be considered during the design stage of adhesively bonded joints.

2. Significant variations were observed in impact strength of the joint when the different adherent was used to adhesively bonded joints. It has been seen that the free surface energy of materials affects directly their bonding strength. Furthermore, materials which have high free surface energy showed higher strength values. The highest impact strength was obtained in stainless steel adherent while the lowest value was obtained in aluminium adherent.

3. The optimum adhesive thickness was obtained at 0.3 mm in copper materials for high impact strength. Also, the higher impact strength values in aluminium adherent were measured at increased adhesive thickness.

4. The ANN model can be used as estimation techniques to predict the impact strength of the adhesively bonded joints.

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