A Study on the Role of Adhesives in Weld-Bonded Joints

Stresses in weld-bonded joints with adhesives of different elastic moduli and thicknesses are obtained by a three-dimensional finite element method

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ABSTRACT. Using a three-dimensional finite element analysis (FEA) method, the effect of elastic modulus and thickness of adhesives on the stress distribution in weld-bonded joints was studied to address the role of adhesive layer. Normal stress and shear stress distributed at the edges of a spot weld and in the lap region were computed for weld-bonded joints made with adhesives of different elastic moduli or thicknesses. The results showed great stress concentration at the edge of the spot weld in weld-bonded joints when the adhesive layer was thick or had a low elastic modulus. Shear stress values in adhesive layers were low under the same circumstances. Stress concentration around the spot weld was reduced and the shear stress in the adhesive layer was increased by increasing the elastic modulus or decreasing the thickness of the adhesive layer. An adhesive layer with appropriate thickness and elastic modulus is necessary to obtain reasonable distribution of stresses in the whole lap region of a weld-bonded joint. A thin adhesive layer of high elastic modulus is favorable to the fatigue properties of weld-bonded joints, and it is recommended on certain conditions.

Introduction

Weld bonding is an advanced hybrid technology that has the advantages of spot welding and adhesive bonding combined (Refs. 1–5). The stress concentration at the periphery of spot welds is reduced and the fatigue performance of the joints is significantly improved by the application of an adhesive. The corrosion problem in the inner surface of the joint's lap region is successfully solved at the same time. Compared with adhesive-bonded joints, the tearing strength of weld-bonded joints is superior and joint reliability is favorable. At present, due to the excellent mechanical properties of weld-bonded joints, weld bonding has been used widely in the aviation and space-flight fields and on the production lines of automobiles.

In weld-bonded lap joints, both the spot weld and the adhesive layer contribute to the joint strength. The load-bearing capability of the two constituents and the stress distribution in weld-bonded joints are determined by many factors, such as the shape and size of the joints and the mechanical properties of the adhesive and base metal. Many experimental results showed the properties of adhesives used in weld-bonded technology have important effects on fracture mode and load-bearing capability of the joints. The experimental results have been analyzed qualitatively from the point of view of joint stiffness, but they have not been interpreted quantitatively. In the present investigation, a three-dimensional elastoplastic finite element method was used to study the effect of the elastic modulus and the thickness of the adhesive on stress distribution in weld-bonded joints. The relationship between the stress distribution and the fracture mode, together with the joint strength, were considered here. The conclusions drawn have instructional significance for designing weld-bonded joints, choosing the adhesives and expanding weld-bonding technology.

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KEY WORDS

Weld Bonding
Elastic Modulus
Finite Element Method FEM
Stress Analysis
Stress Distribution
Joint Strength
AISI 1010
Resistance Welding
Adhesive Bonding

Computational Model and Properties of Materials

Generally, weld-bonded structures and specimens for joint strength testing are made in lap joint configuration. Hence, a weld-bonded lap joint with a single spot was analyzed, as shown in Fig. 1. The tensile shear loads were applied at the two ends of the joint. Electrode indentations were not taken into account in this finite element model. The joint was well bonded, and no defects, such as cavities or inclusions, were located at the interface. In addition, it was supposed the spot weld and the heat-affected zone (HAZ) of the joint had the same mechanical properties. Since the specimen was symmetric about the x- axis, only half of the specimen was considered. The finite element meshes used in the computation are shown in Fig. 2. Three-dimensional brick elements were used. Both the upper and the lower plates were divided into two layers. The adhesive layer included two layers of meshes. The zones near the edges of the lap region and the spot weld were divided into finer meshes because the stresses in those zones were the main concern. The minimum size of the mesh was 0.15 mm. Overall, 1808 elements and 2471 nodes were included in the mesh. Mechanical properties of materials used in computation are listed in Table 1. The base metal was 08Al steel (corresponding to AISI 1010, with chemical compositions of 0.06% C, 0.1% Si, 0.23% Mn, 0.004% P, 0.016% S, 0.04% Al and 0.05% Cu), which is used in the manufacture of automobile structures. The ALGOR elastoplastic FEA program was used to compute the stresses in the weld-bonded joints, which were made using adhesives with different

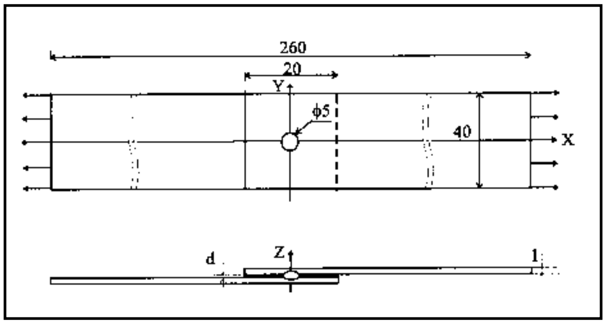

Fig. 1 — Shape and dimensions of the specimen for finite element analysis.

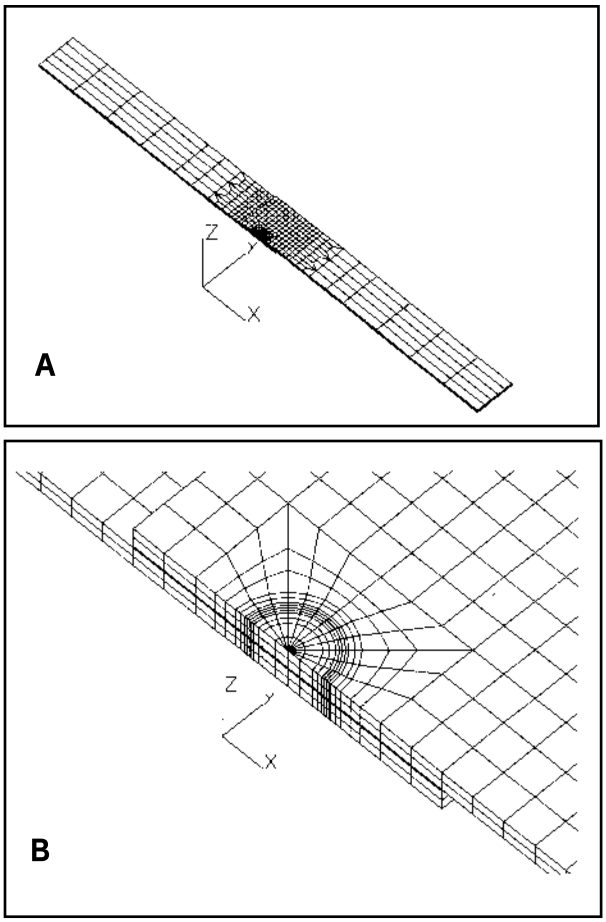

Fig. 2 — Finite element mesh of a weld-bonded lap joint. A — Finite element meshes for the whole joint; B — enlarged meshes for spot weld and lap region.

elastic moduli and thicknesses. The applied loads were equal to 2.5 kN, with an average tensile stress of 125 MPa predicted by materials strength theory.

The joint was only lightly deformed. Only material nonlinearity arising from elastoplastic behavior of materials was taken into account in the computation, while the geometrical nonlinearity caused by a large displacement and strain was neglected. All computation was accomplished on an IBM microcomputer.

Results and Discussions

Effect of Elastic Modulus of Adhesive on Stress Distribution

It was reported that the elastic modulus of the adhesive has more evident effect on the strength of weld-bonded joints than does the adhesive toughness (Refs. 6–9). The weld-bonded joints, made with either toughened or nontoughened epoxy adhesives, had almost the same strengths. Great differences were found between the mechanical properties of weld-bonded joints made with toughened epoxy adhesives and high modulus and joints made with acrylic adhesives and low modulus. When weld-bonded structures are tested under conditions of high or varying temperatures, the modulus of the adhesive will change. It is well known that the stiffness of joints is mainly determined by the elastic modulus if the section areas of the specimens do not vary. Therefore, the elastic modulus of the adhesive can be used to characterize the deforming ability of the weld-bonded joint; that is to say, weld-bonded joints with a low modulus are easier to deform than those with a high modulus.

Stress distribution curves were drawn to make it clear how the elastic moduli of the adhesives affect the stresses in the weld-bonded joints. Generally, the adhesive layers were considered to be fractured by the shear stress at the edges of the lap regions. Radial stress at the periphery of the spot weld was the determining factor for the fracture of a spot weld. Fatigue strength of weld-bonded joints was mainly determined by the maximum radial stress at the edges of the spot weld and lap regions, so that σ_x, the normal stress in x direction, and τ_{zx}, the shear stress at the edges of the spot weld and the lap region, were investigated.

The normal stress σ_x and shear stress τ_{zx} at the edges of the lap region are shown in Fig. 3. The stresses are distributed in the direction of the plate width. It can be seen in Fig. 3A that the normal stress σx decreased with the increase of Y for all five types of adhesives with a range of the elastic moduli from 50 to 200,000 MPa. A high σ_x existed in the middle part of the specimen and a relatively low σ_x at the two edges of the specimen. For joints with a high modulus, the σ_x was lower than in joints with a low modulus. When the elastic modulus of the adhesives equalled 50 MPa, remarkable stress concentration was found at the middle part of the weld-bonded joints, which may have been a response to the spot weld in the joint. With an increase of the adhesive's modulus, σ_x in the middle of the plate decreased, and the stress concentration also decreased.

Shear stresses had uniform distribution along the plate width for all five moduli, and a slight drop of shear stress was observed at the plate edge. The higher the modulus, the higher the shear stresses in the adhesive layers.

Stress curves at the periphery of the spot welds are illustrated in Fig. 4, the abscissa of which is the angular degree of θ. The θ is defined in Fig. 5. It can be found from Fig. 5 that the angular range of 0 deg $\leq\theta$ $\leq$180 deg corresponds to the upper half of the spot weld, the part where 0 deg $\leq\theta\leq$90 deg was the loaded side of the spot weld, and the part where 90 deg $\leq\theta\leq$180 deg was on the load-free side.

From Fig. 4, it was found when the elastic modulus of the adhesive was greater than 500 MPa, the normal stress

Table 1 — Mechanical Properties of Materials Used in the Element Analysis

Materials	Elastic Modulus E, MPa	Poission's Ratio ν	0.2% Yield Strength σ_y, MPa	Hardening Modulus E_t, MPa	Shear Modulus G, GPa
Base metal	190,000	0.25	160	2000	76.0
Spot weld	200,000	0.20	450	1800	83.3
Adhesives	50 ~ 50,000	0.42	90	50	1.76e-2 ~ 17.6

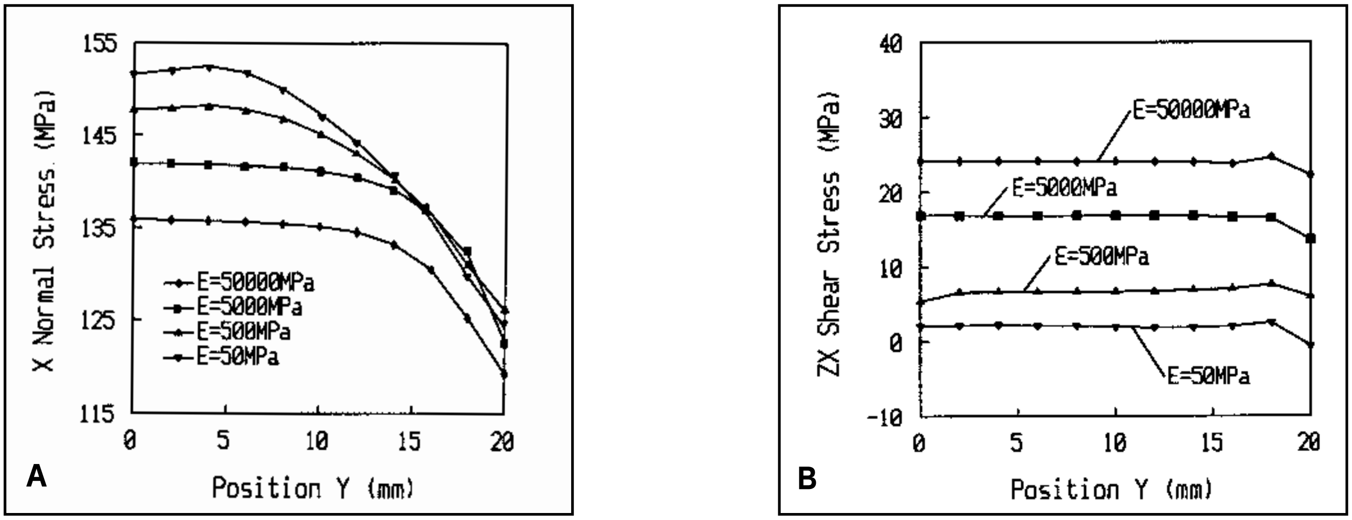

Fig. 3 — Distribution of stresses at the edge of the lap region along the plate width for weld-bonded joints with different elastic moduli. A — Distribution of σ_x along the plate width; B — distribution of τ_{zx} along the plate width.

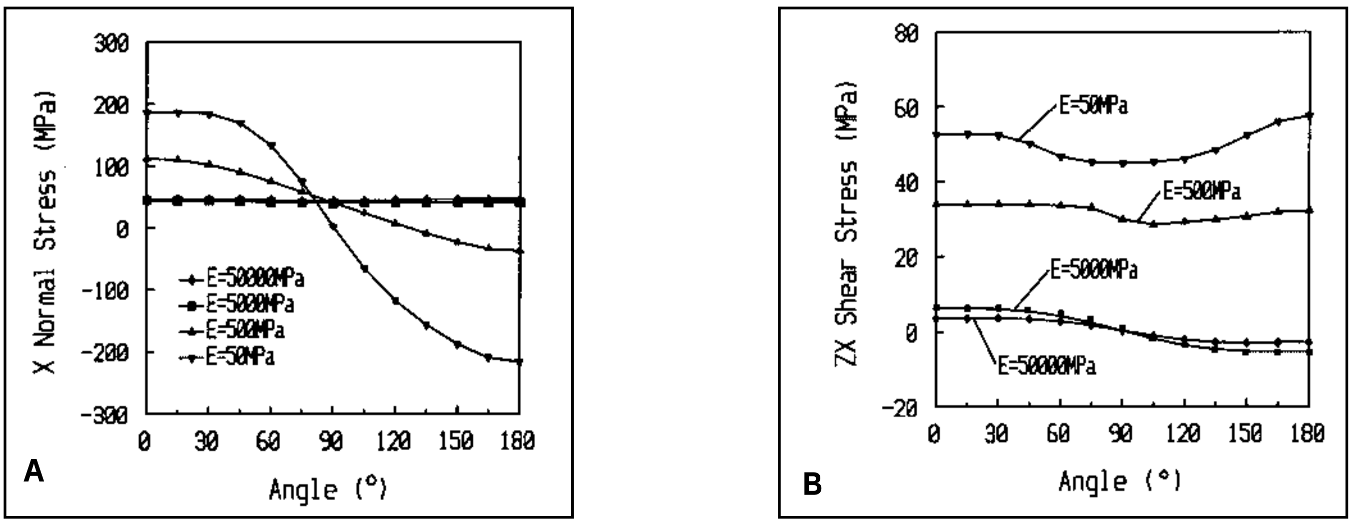

Fig. 4 — Angular distribution of shear stresses at the periphery of spot weld in weld-bonded joints with different elastic moduli. A — Angular distribution of normal stress σ_x; B — angular distribution of shear stress τ_{zx}.

σ_x was low and had uniform distribution over the whole angular range. When the modulus decreased, the stresses around the spot weld were no longer uniform. The tensile stresses σ_x on the loaded side increased and the σ_x on the free side changed from tensile to compressive. The maximums of both tensile stresses and compressive stresses increased with the decrease of the adhesive modulus. For the weld-bonded joints with an adhesive modulus of 50 MPa, distinct stress concentration appeared at the edge of the spot weld.

Shear stresses at the edges of the spot weld were small for weld-bonded joints with adhesives of high elastic moduli. When the elastic modulus of the adhesive was greater than 5000 MPa, the maximum shear stress was lower than 20 MPa. The shear stresses increased when the moduli of the adhesives decreased, which implied the spot weld bore more of the shear load.

From the stress distribution laws mentioned above, it can be concluded the elastic modulus of adhesive has an influence on the stresses in weld-bonded joints. When the elastic modulus is low, shear stresses in adhesive layers were small and significant stress concentration was observed at the edge of the spot weld. With the increase of the modulus, stresses at the edge of the spot weld decreased and shear stresses in the adhesive increased a little. This was because when the moduli of the adhesives decreased, joint stiffness became small and the joints deformed more easily. The applied loads were mainly borne by the spot weld, and stresses distributed in the adhesives were a small part of the total loads, which resulted in high normal stress σ_x and shear stress τ_{zx} in the spot weld zone. Joint strength was considered from the point of view of stress distribution. Stress concentration occurred in the weld-bonded joints with low elastic modulus, and high shear stresses were found at the edge of the lap regions for joints with adhesives of high elastic modulus. When the adhesive modulus decreases, the fracture mode of weld-bonded joints will transform from fracture in the adhesive layer first to fracture in the spot weld (Ref. 10). The adhesive layer and the spot weld have different strengths. A reasonable stress distribution can be obtained by using an adhesive with suitable modulus, whereby the adhesive layer and the spot weld reach the fracture stresses at the same time. For this reason, it is useful and

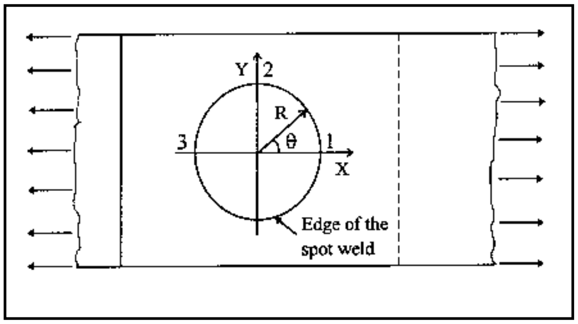

Fig. 5 — Schematic of a spot weld in the lap region of a weld-bonded joint.

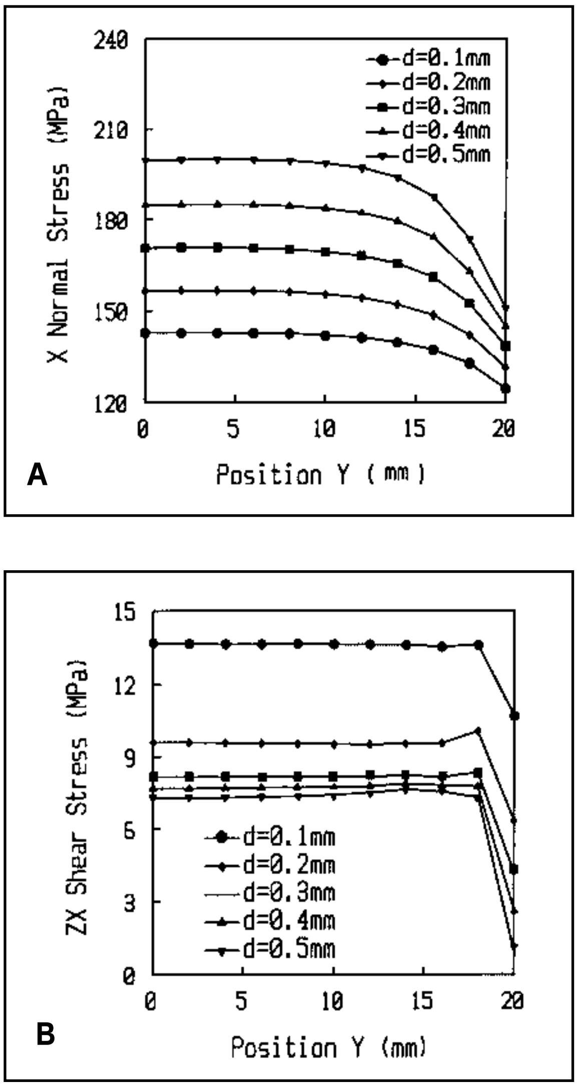

Fig. 6 — Distribution of stresses at the edge of the lap region along the plate width for weld-bonded joints with different adhesive thicknesses. A — Distribution of σ_x along the plate width; B — distribution of τ_{zx} along the plate width.

important to select adhesives with a specific elastic modulus.

Effect of Thickness of Adhesive Layer on Stress Distribution

Under production conditions, the thickness of the adhesive layer is influenced by such technological factors as the assembling and fixing of adherents, the quantity of adhesives and methods of applying adhesives. The thickness of the adhesive layer can vary in a range from 0.1 ~ 1.0 mm. So far, not many experiments or computations have been done to study the influence of the adhesive thickness on the joint strength. The 3-D elastoplastic FEA method was used in this study to gain insight into the relationship between the stress distribution and the adhesive thickness. A phenolic resin adhesive was used in the computation, which has a modulus of 2875 MPa.

Curves of normal stress σ_x and shear stress τ_{zx} distributed along the plate width are shown in Fig. 6. It can be seen from Fig. 6A that σ_x has the same distribution tendency for five adhesive layers with different thickness (0.1, 0.2, 0.3, 0.4 and 0.5 mm). The σ_x distributed uniformly in the middle part of the width, which was greater than that at the two edges of the joints. In the whole range of the plate width, the σ_x increased with the increase of the adhesive thickness and the σ_x in the middle part had a greater increase than that at the two edges. Figure 6B indicates shear stresses distribute uniformly along the plate width and decrease near the plate edges. The shear stresses over the whole range of plate width decreased with the increase of the thickness of the adhesive layer.

Stresses of σ_x and τ_{zx} around the spot welds are plotted in Fig. 7 for five weld-bonded joints with different thicknesses of adhesives. The σ_x distributed uniformly and the stress differences between the loaded side and the free side of the spot weld were small (about 8 MPa) when the adhesive layers were thin. For greater adhesive thickness, σ_x of the loaded side increased while that of the free side decreased; then the differences became greater (about 80 MPa). It is shown in Fig. 7B the shear stresses τ_{zx} on the loaded side of the spot weld were higher than that on the free side. Near the zone of $\theta = 120$ deg, the shear stresses had the minimum values. The shear stress increased with the increase of the adhesive thickness, and the distribution pattern did not vary.

Similar to the adhesive modulus, the thickness of the adhesive layer has a clear effect on the stress distribution in weld-bonded joints. When the adhesive layer was thick, stress concentration around the spot weld was evident. When the adhesive layers became thinner, the normal and shear stresses around the spot weld decreased and the shear stresses in the adhesive layers increased slightly. The phenolic resin adhesive has an elastic modulus of 2875 MPa, which is much lower than 200,000 MPa of the modulus of the base metal 08Al. The restraint from the base metal to the adhesive layer decreased with the increase in the thickness and the stiffness of the joints decreased at the same time. Then a larger deformation will occur in the adhesive layers for the same loads applied. More loads were borne by the spot weld, and higher normal and shear stresses were found there. Normal stress σ_x at the edge of the lap region increased with the adhesive layer thickness because of the larger deformation of adhesive layer in the loading direction, while the shear stress τ_{zx} there decreased because of a smaller restraint on angular deformation of the thicker adhesive layer. For weld-bonded joints with thin adhesive layers, fracture was generally initiated at the edge of the lap region of the joints. The fracture mode will transform from fracture in the adhesives to fracture in the spot weld with an increase in adhesive layer thickness (Ref. 10). It is very important for improving the joint fatigue strength and optimizing the stress distribution to design and produce weld-bonded joints with a suitable thickness of adhesive.

The application of adhesives with the spot welding process greatly reduces the stress concentration around the spot weld and improves the fatigue strength of the joint, with the degree of the reduction and the improvement being dependent on the properties of the adhesive (Refs. 11–12). In this study, it was found stress concentration around the spot weld was reduced when the elastic modulus in-

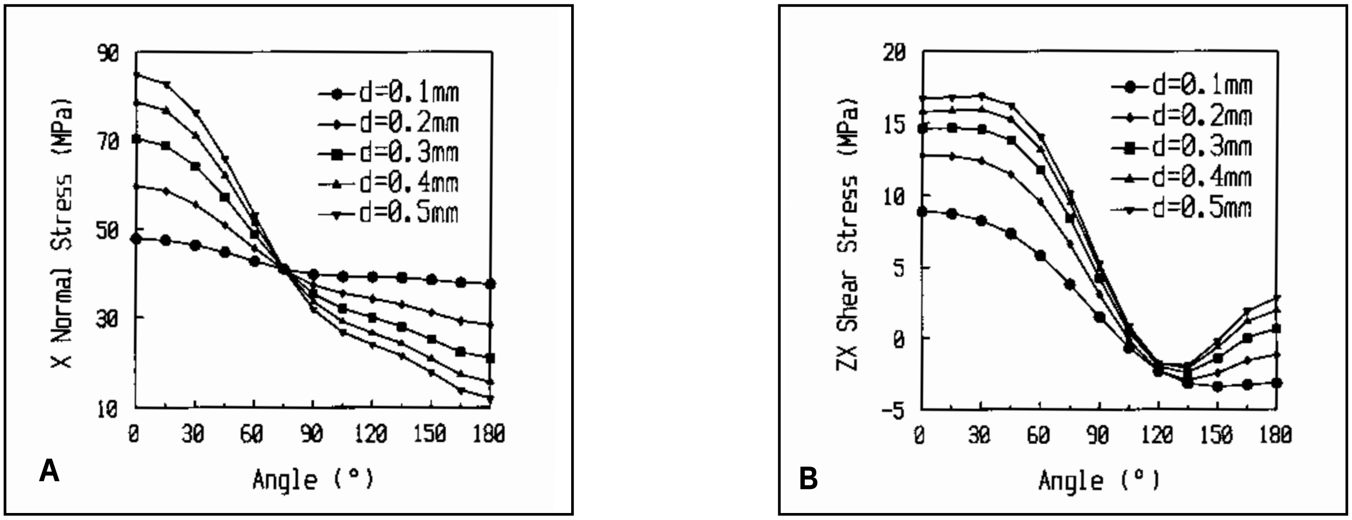

Fig. 7 — Angular distribution of stresses at the periphery of the spot weld in weld-bonded joints with different adhesive thicknesses. A — Angular distribution of normal stress σ_x; B — angular distribution of shear stress τ_{zx}.

creased or the thickness of the adhesive layer decreased. The shear stress values located at the edge of the lap region are less than 60 MPa, although greater shear stresses were found also. The dominant controlling factor for the joint's fracture was the normal stress σ_x in this circumstance; therefore, a thin adhesive layer with a high modulus was favorable for the fatigue property in weld-bonded joints. Of course, when the adhesive layers are too thin, the joints cannot be bonded well. Some technological problems will be caused when the elastic modulus of the adhesive is too high, such as the difficulty with displacing the adhesive layer beneath the welding electrodes and the insulating effect of the adhesive layer on the spot weld. These factors must be taken into account in choosing the type of adhesive and designing the thickness of its layers.

Conclusions

In the present study, a three-dimensional numerical analysis model was developed for weld-bonded joints. Normal and shear stresses in the joints with different adhesives were computed. Relationships between stress distribution and elastic modulus and thickness of adhesives were discussed. From this work, the following conclusions are drawn:

1) In the model developed, indentations were ignored and the joint was thought to be bonded well. In addition, the HAZ was considered to have the same mechanical properties as the spot weld. Results obtained in previous studies showed that these assumptions have a negligible impact on computation results.

2) Stresses around the spot weld increased with the decrease in the elastic modulus of the adhesive. Great stress concentration was found when the elastic modulus of an adhesive was lower than 100 MPa. The stress concentration around the spot weld was reduced by using adhesives with a high elastic modulus, but greater shear stress was found at the edge of the overlap region.

3) Stresses in weld-bonded joints were influenced by the thickness of the adhesive layer. Greater normal stress and smaller shear stress were found at the lap edge for weld-bonded joints with a thick adhesive layer, and magnitudes of both normal and shear stresses around the spot weld increased with an increase in adhesive layer thickness.

4) It was found that an adhesive layer with a high elastic modulus or small thickness will cut down stress concentration in weld-bonded joints and improve the fatigue strength of the joint. Hence, a thin adhesive layer with high elastic modulus is recommended because the joint can be bonded well and no technological problem is encountered in its production.

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