The Effect of Nanoparticles in Single-Lap Joints Studied by Numerical Analyses

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Abstract — The present study concerns with the finite element investigation of balanced aluminium single lap joints subjected to tensile loading. Epoxy adhesives were used for bonding having different nanoparticles rate in the epoxy resin (0.5, 1.0, 1.5 and to 2 wt. %, respectively). Two-dimensional (2D) finite element analysis has been employed to determine the peeling stress, von Mises stress, and the shear strain distribution across the midplane of the joints. The results mainly prove that the nanoparticles rate in the adhesive material directly affects the joint tensile strength. Nanocomposite adhesives present a higher failure load than that of neat adhesives. Furthermore, nanocomposite adhesive with 0.5 wt. % of nanoparticles generated strengths (shear and peeling strengths) more than neat adhesives, after which decreased by further addition of the nanoparticles.

Index Terms — Aluminium, Alumina nanoparticle, Finite element analysis, Single lap joint.

I. INTRODUCTION

Adhesive bonding is a material joining process in which an adhesive, placed between the adherend surfaces, solidifies to produce an adhesive bond. Research on adhesives has a long tradition, and has many advantages over other methods of fastening (bolts, rivets and pins), such as fast and easy disassembly as well as the insensitivity to temperature or moisture operations [1], [2]. It should be mention that mechanical joints cannot distribute the load uniformly and causes stress concentration [3]. A number of works have shown that this problem is usually overcome by using adhesively bonded joints. In comparison with other techniques, adhesively joints have the advantage of lighter structures, having fewer points of stress concentration as well as, superior fatigue and environmental resistance [4]-[7]. Adhesive for bonding structures is growing more and more, because they present a smooth exterior and ease joining thin or dissimilar materials [8].

Adhesively joints have been widely adopted in the field of aerospace and automotive industries [9], [10], but the performance of structural adhesives varies because of their poor mechanical properties. It is clear that the problem could be easily tackled by using thermoplastic compounds [11], [12] or inorganic particles [13]-[17], but such improvements are limited in some cases.

It would be of special interest of using nanotechnology to the adhesive industry [18]. There has been less previous evidence for nano scale materials where could enhance the performance of adhesives [19]-[23]. The literature review shows that polymer nanocomposites are among the most promising materials. Exhibits better properties than polymer composites and their corresponding conventional fillers [24]-[35]. A number of questions regarding on nanoparticle dispersion and the interfacial interactions between the nanoparticles and the polymer matrices, remain to addressed [36], [39]. Dispersion seems to be a common problem in nanotechnology [19], [40]-[46].

There have been numerous studies to investigate nano-reinforced adhesives by using reinforcements in epoxy resin [47-49]. The results confirm that this a good choice for improving the mechanical resistance of structural joints [50], [51] as well as the wetting capability [52], [53]. The enhancement of the mechanical performance of the epoxy adhesives can directly be related to the improved shear strength of nano-reinforced joints [54]. Unless there are micro-voids between adherent surface and the adhesive layer. Nanofillers could penetrate into the micro-voids and enhance the joint strength by mechanical interlocking [55].

The adhesive properties can be modified by nanoparticles, which are added to increase the performance of the adhesive [23, [56]-[64]. However, this improvement is limited in some cases [65]-[67].

Experimental studies have been also reported on development of nanocomposite systems. As already mentioned, adhesive joints can improve their properties by adding nanoparticles such as Al2O3 and TiO2 into structural adhesives with different properties under tensile load [68]. The results demonstrate that the tensile damage load as well as the displacement capacities were increased with the connections obtained by using compounds of nanoparticles. At the same time, SiC particles at different ratios were used to produce composite plates [69]. By using SiC particles, the strength and the elongation of the plate was increased.

A large number of existing studies in the broader literature have examined also the strength and durability of adhesively bonded joints with carbon fiber (CNT) [16], [70], hybrid carbon fiber (CNF) [71, 72] and graphene nanoparticle (GNP) [73, 74, 75] epoxy adhesives. Hybrid joints improves the properties of the joints. However, there are studies which prove that such joints, decrease the strength of the joints [76]-[78].

Finite element method is another useful tool in order to analyze adhesively joints. In recent years, some exciting developments of FEA of adhesive bonding as a function of wt. % of nanoparticles have been accompanied by scientific
research by many researchers [79]-[81]. Based on a two-dimensional FEA, the maximum shear stress was observed in adhesive region near to the adherent with higher stiffness [82]. However, interfaces are also critical regions, and stress should be calculated [83]. Wu and Crocombe [84] show that the stress distribution along the bond line of single lap joint can be investigated by using beam elements and quadrilateral elements for adherends and adhesive, respectively. Their paper results might have been more interesting for a range of material properties of different types of adhesive joints.

Finite element analysis also has been used to determine the shear stress in an adhesively bonded single-lap joint [85]. Sayman uses materials such as a glass fiber epoxy composite and DP460 as an adherend and adhesive, respectively. The results were in a good agreement with the analytical elastoplastic stress analysis.

In a recent study, He [86] explained the effect of boundary conditions on the stress distribution of adhesively bonded single lap joint. The results from his analysis appear to confirm that stress concentration was confined to a very small region near or at the free ends of overlap interfaces between the adherend and the adhesive layer. However, at the center of the glue line thickness was observed free of stress concentration.

A multiscale formula was developed in order to analyze glass powder (150 µm) reinforced adhesive joints by Reina-Romo and Sanz- Herrera [87]. Moreover, a nanoscale representative element was developed by Wernik and Meguid [88]. They focus on the dispersion of the reinforcing element into the bulk adhesive.

Most of the reported literatures [82]-[86] on finite element analysis of adhesively bonded joints are limited to neat adhesive. To the best of authors knowledge, the FEA of adhesively bonded single lap joint reinforced with nanoparticles has been rarely studied.

The present study describes the parametric investigation of adhesive bonded aluminum-to-aluminum lap joints subjected in tension. Two-dimensional (2D) finite element analysis has been employed to determine the peeling stress, and the shear strain distribution across the midplane of the single-lap joints. The von Mises stress distribution also evaluated. In the sequence, finite element results are presented in detail and compared with the additional experimental results from literature. The simulation of adhesively bonded joints reinforced with nanoparticles has been carried out using Comsol Multphyics. The results obtained from finite element analysis were compared with the additional experimental results.

II. JOINT CONFIGURATION AND MATERIALS

A. Joint Configuration

The testing configuration was based on the ASTM standards D 1002-01 for metal-to-metal single-lap joints. A typical test specimen configuration is shown in Fig. 1. The main objective is to transfer the load smoothly from one adherent to the other, while increasing the overlap length the maximum peel and shear stresses were minimized in the middle of the overlap region [89], [90].

In this context, in order to investigate the influence of the nanoparticle rate, a 13 mm overlap length was selected. All dimensions were kept constant (Fig. 1), while the thickness of the adhesive was 0.25 mm.

![Fig. 1. Typical test specimen configuration based on the ASTM standard D1002 [89].](image)

B. Materials

Adherend material was Aluminium 2068 with 2.0 mm thickness was selected, while five different Young’s modulus of adhesive layer have been used for bonding. The mechanical properties of the materials are given in tables 1 and 2. It was previously mentioned that the alumina nanoparticle (AluC) rate varies from neat to 2.0 wt. %, Studies have emphasized [91] that alumina nanoparticles improve elastic modulus (in this study up to 1.5%), but more than that, there is a slight reduction of the properties of the adhesive layer.

| TABLE I: ALUMINIUM 2068 PROPERTIES |
|-------------------------------------|
| Material | E (GPa) | ν | ρ (kg/m³) |
|-----------|---------|---|----------|
| Aluminium | 70      | 0.06 | 2700 |
| Tensile Strength (GPa) | 25.40 |
| Yield Strength (GPa) | 7.20 |

| TABLE II: ADHESIVE PROPERTIES [91] |
|------------------------------------|
| Material | E (GPa) | σb (MPa) | εb (%) |
|----------|---------|---------|--------|
| Epoxy    | 1.95    | 34.2    | 2.5    |
| Epoxy+AluC-0.5% | 2.12 | 43.1    | 3.5    |
| Epoxy+AluC-1.0% | 2.23 | 38.6    | 3.1    |
| Epoxy+AluC-1.5% | 2.44 | 39.6    | 2.9    |
| Epoxy+AluC-2.0% | 2.16 | 34.0    | 2.8    |

σb is the tensile stress, εb is the deformation at break

III. FINITE ELEMENT ANALYSIS

Finite element simulations were carried out by using Comsol Multiphysics. Eight elements were placed across the thickness of the adhesive. For a constant number of elements, one can compare between the five different Young moduli’s, while the adhesive thickness was assumed to be constant.

Since the joint width is much greater than the thickness, a plane strain condition was assumed, but it is well known that the stress state is three dimensional. The assumption of plane strain will not be valid at all locations within the joint. Furthermore, the bond was assumed perfect and free from defects (i.e. voids).
Adherend material presumed to be elastic is intentionally given high initial yield stress value since the focus is on the behaviour of adhesive material. The displacement is applied incrementally so that the stress-strain distribution monitors the increasing of displacement, thus enabling the plasticity equations to be solved correctly. The boundary conditions are illustrated in Fig. 2. To avoid the possibility of convergence a non-linear finite element analysis is needed. According to Fig. 3, when the joint is subjected to axial load (displacement), a rotation occurs at the ends of the joint. Furthermore, axial load relieves the bending moments at the end of the joint. At the ends of the overlap zone, a high stress gradient is expected to occur, and these critical regions were refined until reasonable results were obtained. Adherends should remain elastic, while the longitudinal strain is less than 0.3%.

![Fig. 2. Boundary conditions.](image)

For the adhesive, a von Mises criterion may be used which includes a component dependent on the hydrostatic stress. In the present study the adhesive material were assumed to have a non-linear elastic behavior. A representative stress-strain curves are shown in Fig. 4.

![Fig. 3. Adhesive joint rotation subjected to axial load.](image)

![Fig. 4. Representative stress–strain curves of Epoxy-AluC nanocomposites](image)

IV. RESULTS AND DISCUSSION

The peel stress, von Mises stress, and shear strain curves of the nano-adhesive joints as a function of AluC content are shown in Fig. 5 (a)–(c). The variation of the peel stress distribution for five different Young’s moduli’s of the adhesive while the overlap length kept constant at 13 mm can be seen in Fig. 5a. Along the length of the overlap, a large area exists where the adhesive is under hydrostatic compression (less than 2 mm for each side). The highest peel stresses are noticed 2.9 mm further away from the overlap edge. As the amount of the nanoparticles increases up to 0.5 wt. %, the peel stress increases (45.6%). At the edges of the joint the load from one adherend to the other mainly carried by tensile stresses, where the plasticization effect is more accentuated at the edges [92], [93]. The peel stress is more localized and is introduced by the rotation and bending of the adherends. The peak value of the peel stress is decreasing with the increase of the percentage of nanoparticles.

The maximum peel stress for the adhesive is 82.68 MPa (almost at the ends) and is considered to dominate the failure of the joint [94]. The influence of altering the amount of nanoparticles more than 0.5 wt. %, it could be considered as a convenient way to minimize the peak stresses at the adhesive ends. On the other hand, it can be seen from Fig. 5b, that von Mises stresses are higher than peel stresses (avg. 41%). That means the tensile load is carried by the overlap length and not only by its edges. Furthermore, the plastic region shifts further away from the edges (0.1 mm) while at the center of the overlap length the von Mises stress is higher at least 350% compared with the peel stress.

According to Fig. 5c, the maximum shear strain is located as the ends of the joint and depends on the rate of the nanoparticles in the epoxy matrix. The strain curve clearly shows that increasing AluC nanoparticles more than 0.5 wt. % leads to a decrease of the shear strain.

To be more specific, in the range of 0-0.5 wt %, the shear strain of the joints was increased, from 2.66% to 3.55% (an increase of 33.4%), but in the range from 0.5-1.5 wt %, the shear strain decreases from 3.55% to 2.72% (a decrease of 23.38%). The results show that an important parameter is the stress transfer between nanoparticles and polymer matrix which improve the adhesion properties of the adhesive bond.

It is also likely that for amount more than 1.5 wt. %, the shear strain increases almost 3.3%. Maximum shear strains act on a very small area of the joint (load transfer zone), 0.2 mm away from overlap edges.

Furthermore, shear strain is less developed in the center of the overlap zone, but for case of 1.0%, the shear strain is quite high at the middle of the joint (almost 31% compared with the neat adhesive). That means, the area is mainly loaded in shear, especially as the overlap length increases. In other words, there is a large portion of the bond length which is mainly loaded in shear [89], [90].

From Fig. 5a-c, it can be observed that stresses are symmetric about the center of the overlap and reach a maximum at the ends of the overlap [95], [96]. It should be noted that interfaces are also critical regions and must be studied deeply [89], [90].

Finally, the present study confirmed the experimental findings about deformation at break as a function of nanoparticle content (Fig. 6).

From the results, it is clear that the peeling stress and shear strain depends on the amount of nanoparticle in the adhesively joint. As the amount increases, adhesively joints increase their strength. This is due to the ability of the nanoparticles to fill any microscopic gaps present in the adhesive as a result of their dispersion, and mechanical interlocking. However, there is a limit to the number of dispersed nanoparticles.
The following conclusions can be made:

- The nanoparticle content up to 1.5% improves the elastic modulus but more than that, there is a slight reduction of the elastic modulus (experimental procedure). The mechanical properties of the adhesive reinforced by Silica nanoparticles, in particular, its Young's modulus depends on the rate of the nanoparticle.

- The maximum peeling stress, the von Mises stresses as well as shear strain occur at the edges of overlap length, and for amount of 0.5 wt. % AluC. After that rate stress-strain decreases.

- The strength of the adhesive joints is directly affected by the amount of the nanoparticles.

- By increasing the AluC content, it is similar to increasing the overlap length of the joint, which means that increasing the nanoparticle content is shown to be a good way to produce more resistant joints with lower losses of strength.

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