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Experimental analysis on the single-lap joints bonded by a nanocomposite adhesives which obtained by adding nanostructures

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ABSTRACT

Especially findings from nanoscience and nanotechnology, which have progressed significantly in recent years, influence materials and mechanical sciences deeply as well as other disciplines. In this study, the failure loads of single-lap joints (bonding joints used in space, automotive and aerospace applications) bonded by a nanocomposite adhesive – obtained by adding nanostructure to the adhesive – were experimentally examined to increase the failure load of adhesively bonded joints. Adhesively bonded single-lap joints were produced using DP460 toughened adhesive type, DP270 rigid adhesive type and DP125 flexible adhesive type as the adhesives; AA2024-T3 aluminum alloy was used as the adherend, and Graphene-COOH, Carbon Nanotube-COOH and Fullerene C60 were used as the added nanostructures. Furthermore, to examine the effects of nanostructure reinforcement ratios in the adhesive at joint-failure load, three nanostructures with different ratios of 0.25%, 0.5%, 1%, 2% and 3% were added. As a result, when the experimental failure loads were examined, the nanocomposite adhesives obtained by adding nanostructure were found to have increased the load failure of the joint. However, increase rate in the failure load changes depending on the structural features of the adhesive and the type of nanostructure. Moreover, in the geometries of single-lap joints produced in this study, the best nanostructure reinforcement ratio, in terms of the failure load of the joint, was 1% percent by weight.

1. Introduction

Adhesively bonded joints have been widely used in many areas of technology, including the automotive, marine, space and aeronautics sectors, where their application offers significant advantages. However, in the design of adhesively bonded joints, many problems can appear. One of these problems is that a stress concentration occurs in the free edges of the bonding area. Different methods such as tapering the adherend, forming an adhesive fillet, changing the lap-joint geometry and hybrid double lap exist to reduce these stresses [1–9]. A study carried out by Marannano et al. [5], the mechanical behavior of hybrid bonded/riveted joints were investigated experimentally and numerically. The results indicated that failure load increased 20% for static loading and 45% for high cycles fatigue using steel or aluminum rivets in adhesively bonded joints.

One of these methods is the use of composite adhesives reinforced with nanoparticles [10–14]. In the literature, research on adhesively bonded joints obtained by using composite adhesives reinforced with nanoparticles has been summarized below.

In the study performed by Srivastava [15], the shear features of single lap-joints bonded by adhesives obtained using C/C and C/C-SiC composite materials as the adherend and 3% Carbon Nanotube (CNT) reinforced adhesive were examined. This study found that the reinforcement of adhesives using Carbon Nanotubes increases the toughness and strength of the epoxy resin, and this increases the resistance of adhesively bonded joints to shear deformation and crack formation.

A study, carried out by Kang et al. [16], examined the static and dynamic strength of composite-aluminum single-lap joints produced by using 2% Carbon Nanotube (CNT) reinforced adhesive. In the comparison between the joints produced by using 2% Carbon Nanotube reinforcement and the joints using non-reinforced adhesives, an approximate 36% reduction in the tensile failure load of

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the joints was observed in the former one compared to the latter one. It was thought that the reason behind this reduction is that the carbon nanotube reduces the bond strength between composite and adhesive. When the fatigue strength of the nanostructure reinforced and non-reinforced adhesives was examined, it was seen that the 2% CNT reinforced joints were 13% tougher.

Furthermore, a study carried out by Garrett et al. [17], emphasized how carbon nanotube reinforcement in epoxy adhesive affects the Mod II rupture strength of steel composite and composite-composite bonding applications. It was observed that in all samples, the distribution of the Carbon Nanotubes in the adhesive had an impact on the rupture features. It was found that the nanotube's features of carboxyl group, dispersion, structure, length and diameter all play an important role in determining whether the nanotube reinforcement strengthens or weakens the joint, and as the result of the tests, the optimum nanotube reinforcement should be around 1%. In the composite-composite adhesively bonded single-lap joint, adding 1–5% multiple walled CNT to the adhesive increases the shear strength at a rate of about 46% [18].

In the adhesively bonded joints, adding different nanostructures to the adhesive (nano clay, nano Al_2O_3, nano $CaCO_3$, nano SiO_2 etc.) affects the failure load of the joint in the same way as adding Carbon Nanotubes to the adhesive does [19–22].

In the study performed by Zhai [19], the effects of surface roughness in the bonded joints obtained by adding different amounts of Al_2O_3 nanoparticles, with an average diameter of 80 nm, to the adhesive was analyzed. In the study, an increase of up to five times the joint strength was observed in 2% reinforced joints when it was sandpapered with 150 grit sandpaper, and an increase of up to two times was observed when it was sandpapered with 60 grit sandpaper. If it is accepted that rough surfaces will increase the bonding strength by increasing the area of interaction, it can also be thought that Al_2O_3 nanoparticles cause a similar effect. In addition, nanostructures greatly increase the joint strength of bonding joints that are obtained by the addition of Al_2O_3, $CaCO_3$ and SiO_2 nanostructures having diameters of 80 nm, 40–80 nm, and 10–20 nm, respectively. The best results in joint strength were obtained by the addition of Al_2O_3 nanostructures [20].

In this study, tensile failure loads of single lap-joints using nanocomposite adhesives – obtained by adding nanostructure to the adhesive – were experimentally examined to increase the failure load of adhesively bonded joints. In the study, adhesively bonded single-lap joints were produced by using DP460 toughened adhesive type, DP270 rigid adhesive type and DP125 flexible adhesive type as the adhesive; AA2024-T3 aluminum alloy as the adherend, and Graphene-COOH, Carbon Nanotube-COOH and Fullerene C60 as the nanostructure. Joint samples were produced by adding nanostructures at five different percentages by weight (0.25%, 0.5%, 1%, 2% and 3%) to examine the effect of nanostructure reinforcement ratios in the adhesive, on the failure load of the joint. Under the tensile load, the failure mechanisms, displacement abilities and standard deviations of the single-lap joints obtained by using three different adhesives (DP460, DP270 and DP125), three different nanostructures (Graphene-COOH, Carbon Nanotube-COOH and Fullerene) and five different ratios (0.25%, 0.5%, 1%, 2% and 3%) were experimentally determined.

2. Experimental details

In this study, AA2024-T3 aluminum alloy, widely used in aerospace, aircraft, transport and general engineering industries – due to its good mechanical and physical properties – was used as an adherend. For bonding, a two-part paste epoxy (DP460 toughened adhesive, DP270 rigid adhesive and DP125 flexible adhesive type, produced by 3 M Company, St. Paul, MN, USA) was used as the adhesive. For the nanostructure in the adhesive, 0.5, 1 and 2% by weight of Graphene-COOH (thickness 5–7 nm, diameter 5 μm, surface area 120–150 m^2/g), Carbon Nanotubes-COOH (diameter 10–20 nm, length 10–30 mm, purity 95%, surface area 200 m^2/g and COOH coverage 2% by weight) and Fullerene C60 (purity 99%) were added. These nanostructure were purchased from Graphene Chemical Industry (Turkey). Mechanical properties for the adherend and adhesives used in experimental studies are given in Table 1.

The most important point in the preparation of the nanostructure-reinforced adhesives is to distribute the carbon nanostructures homogenously within the adhesive to prevent flocculation between nanostructures. In the study performed by Gültekin et al. [23], the standard deviation in the joint samples obtained by a new method was minimized up to 1%. This new method was developed together with colleagues at the department of chemistry education. Considering this new method, both non-reinforced and nanostructure reinforced adhesives was prepared as follows.

The procedure followed for the preparation of non-reinforced adhesive was as follows:

✓ The epoxy part of the adhesive mixture and approximately ten grams of acetone were added together by using a precision balance in a clean and empty glass, and was then mixed for thirty minutes by an ultrasonic mixer at 30 KHz frequency. (Fig. 1a).
✓ Being kept at a temperature below the curing temperature – at 50 °C – in the drying oven, the acetone in the acetone and epoxy mixture was completely evaporated. To evaporate the acetone much faster, it was sometimes stirred mechanically by hand (Fig. 1b).
✓ The control of complete evaporation of the acetone was done by measuring the amount of epoxy using a precision balance scale.
✓ Then the mixture was stirred for ten minutes by hand, adding the accelerator according to the ratio of epoxy and accelerator compound. (Fig. 1c).

The procedure followed for the preparation of nanostructure reinforced adhesive was as follows:

✓ 0.5, 1 and 2% by weight of graphene is added to the amount of adhesive and approximately ten grams of acetone was added by using a precision balance in a clean and empty glass, and was then mixed for ten minutes by the ultrasonic mixer at 30 KHz frequency.
✓ Then, after adding the required amount of epoxy, it was stirred for thirty minutes by the ultrasonic mixer at 30 KHz frequency.
✓ The acetone was evaporated by keeping the acetone/nanostructure/epoxy mixture at a temperature below the curing temperature – at 50 °C – in a drying oven.
✓ The complete evaporation of the acetone was controlled by measuring the amount of epoxy and nanostructure by using a precision balance.

Table 1
Material properties of the adherend and adhesives.

	AA2024-T3	DP 270	DP 125	DP 460
E (MPa)	70410 ± 615	610 ± 18	25.1 ± 2	1984 ± 43
ν	0.33	0.32	0.35	0.37
σ_t (MPa)	476 ± 17	26.2 ± 0.7	12.7 ± 0.4	38.4 ± 1.1
ε_t (%)	16	5.2	78.5	4.7

E: Young's modulus; ν: Poisson's ratio; σ_t: Ultimate tensile strength; ε_t: Ultimate tensile strain.