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Research Article

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Determination of Shear-strength of Steel Joint Bonded with Epoxy/Nano-Al_2O_3 Adhesive Using Kolsky Bar

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Abstract

The article experimentally analyses the shear-strength of epoxy/nano-Al_2O_3 employing a single lap steel joint. The base epoxy adhesive was adapted by adding 0.5, 1.0, 1.5, and 2.0 wt.% of nano-Al_2O_3 (spherical and rod shapes) using an *in situ* polymerization technique. Reinforcement of spherical and rod nano-alumina is done to improve the lap shear-strength of epoxy adhesive. The optimal wt.% of nano-alumina in adhesive for shear-strength was investigated under static loading using the Kolsky bar system. Static lap shear-strength was witnessed optimum for 1.5 wt.% of rod and spherical nano-Al_2O_3 in the epoxy adhesive. Whereas, the epoxy/nano-Al_2O_3 adhesive holding 1.5 wt.% of nano-alumina was preferred to analyze the shear-strength at high loading rates. The shear-strength was increased with increased loading rates, but increment was comparable lower at high loading rates. Lap shear-strength of joints under high loading rates was observed 2.5 to 6.0 times higher than the static loading. Reinforcement of spherical nano-alumina showed better performance than rod nano-alumina.

Keywords

Adhesive, Shear-strength, High loading rate, Shape of nano-alumina, Single lap-joint

Introduction

The Kolsky bar system is used to test the adhesive joints in the range of 10^2 - 10^4 s^{-1} strain rate [1-13]. Under high strain rate loading, steel sheets bonded with mineral particles filled with single-component epoxy resin were maximal shear-strength at a surface roughness of 1.17 μm [1]. The strength of steel joints bonded with unmodified cyanoacrylate and epoxy-adhesive improved as the loading rate rises [2-13]. However, some literature reported that dynamic shear-strength maintained a constant value when the loading rate was above the ideal loading rate [2-3]. The adherend materials and the adherend combination (similar and dissimilar) largely determine the dynamic strength of the joints (steel and aluminum) [9]. Whereas it is found that the strength of steel-steel joints was more as compared to aluminum-aluminum joints.

Reinforcement of nano-size of particles is one of the methods to advance the mechanical strength of adhesives [13-20]. However, reliable experimental data is required to use the adhesive in industries with confidence. The static strength of epoxy joints modified with nano-alumina, nano-clay, and nano-silica had a higher value compared to unmodified epoxy [13-20]. The inclusion of nano-alumina in bulk epoxy and epoxy adhesive enhanced the strength under high loading rates [13, 21]. At high and quasi-static shear strain rates, the failure load of epoxy/nano-Al_2O_3 adhesives shows a considerable enhancement in comparison to the base adhesive [22, 23].

Materials and Methods

The Kolsky bar is a common system to depict materials at high strain rates. It involves two main long cylindrical elastic bars (incident and transmission). The sample material is kept between these two bars. The striker bar is used to make an impact on the incident bar. This results in an elastic compressive stress which travel through the former. At the junction of the incident bar and sample, this wave is partly reflected, and rest is transmitted into the transmission bar through the sample. The dynamic stress-strain response of the sample is gained by evaluating the pulse shapes for the incident, transmitted, and reflected waves with time [24].

Materials

For the production of the base adhesive, the resin, Araldite LY556®), and hardener, Araldite HY951® are mixed together (10:1 by weight). Adherend material, steel was used having a Modulus of elasticity 210 GPa and Poisson's ratio of 0.3. A schematic diagram of a single lap-joint fabricated following ASTM D905 [22] and an arrangement for fixing in the Kolsky bar is illustrated in figure 1. Spherical nano-alumina (nano-spheres) and cylindrical nano-alumina (nano-rods) were added in the neat adhesive. Al_2O_3 nano-spheres (diameter, 23 - 47 nm) were made available by Nano-structured & Amorphous Materials, Inc., USA. Al_2O_3 nano-rods (length <50 nm and diameter <10 nm) were obtained from Sigma-Aldrich Co, Bangalore, India.

Sample preparation

The schematic diagram for the preparation of epoxy/nano-Al_2O_3 adhesives using the in situ polymerization technique is shown in figure 2. The required amount of alumina nanoparticles and acetone were mixed and sonicated for one hour using an ultrasonicator. Then, the required epoxy resin was dispensed into the mix and again sonicated for 1 hour. The epoxy/nano-Al_2O_3 adhesives were prepared by combining the alumina-reinforced epoxy resin and hardener at 10:1 by weight.

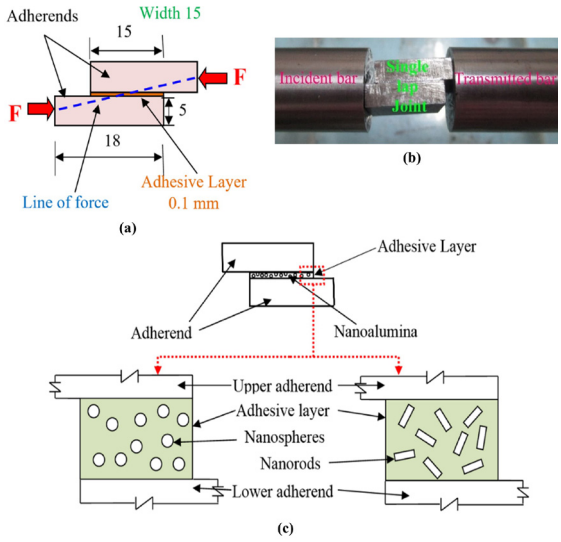

Figure 1: (a) Diagram of single-lap joint (sizes are in mm), **(b)** Placing of joints in Kolsky bar, and **(c)** Representative bonded joint.

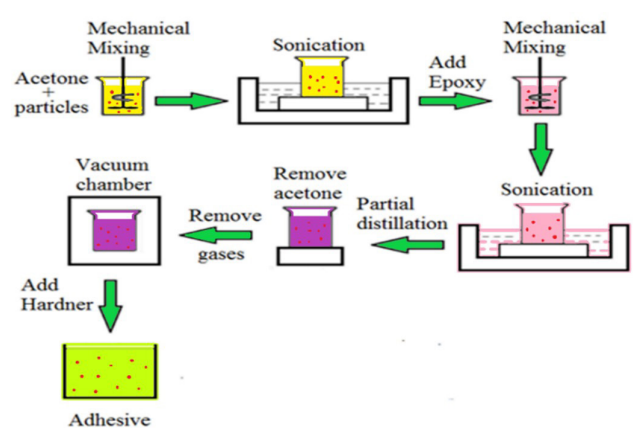

Figure 2: The schematic diagram for the synthesis of epoxy nano-alumina adhesive.

Adherends were adequately cleaned from the dust and grease using a cleaning agent (acetone). Emery grit paper (grit no. #60) is used for roughening of the adherends' joining surface area for improved joint. The average surface roughness of steel adherend was 0.96 ± 0.07 microns. Adhesive layer of thickness 0.1 mm was pondered and smeared on bonding surfaces. Then the uncured joints were cured for 24 hours at room temperature. The edges of the joint were freed from the squeezed-out adhesive to avoid the spew effect. Static tests were done on a UTM (Tinius Olsen, India) following ASTM standard D905. The average static loading rate on joints was 144 N/s.

Results and Discussion

Figure 4 shows the variation in the static lap shear-strength with wt.% of nano-Al_2O_3 for the joints. Error bars represent the 95% confidence interval at each average value.

Reinforcement of Al_2O_3 nanoparticles enhanced the shear-strength of lap-joints. A favourable outcome was ob-

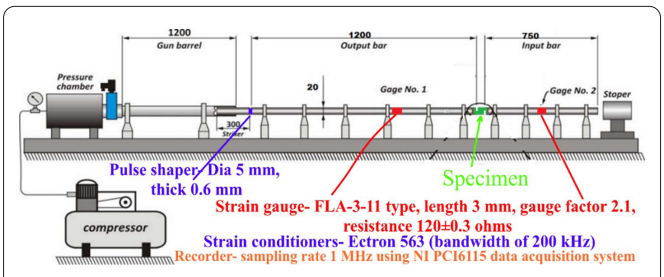

Figure 3: Placing of the specimen (joint) in the Kolsky bar system [23].

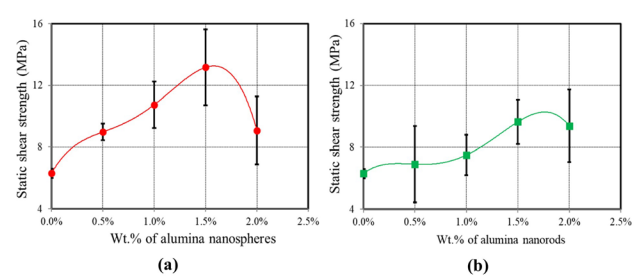

Figure 4: Effect of wt.% of nano-alumina on lap shear-strength under static loading.

served by both types of nanoparticles. But it had an optimal wt.% of alumina nanoparticles. Static lap shear-strength was improved by reinforcing spherical and rod nano-Al_2O_3 up to 1.5 wt.%. Whereas more addition of alumina nanoparticles resulted in diminished shear-strength. So, the shear-strength under high loading rates was analysed for adhesive with 1.5 wt.% of nano-alumina using the Kolsky-bar system. Typical pulse profile and force variation with respect to time are given in figure 5. The transmitted force curve is shown in figure 5b. The slope of the transmitted force is used to analyse the loading rate.

Incident force ($F_1(t)$) and transmitted force ($F_2(t)$) were calculated from incident strain pulse (ε_i), reflected strain pulse (ε_r) and transmitted strain pulse (ε_t) following equation (1) [2].

$$\left.\begin{aligned} F_1(t) &= E_b A_b \left\{\varepsilon_i(t) + \varepsilon_r(t)\right\} \\ F_2(t) &= E_b A_b \varepsilon_t(t) \end{aligned}\right\} \quad (1)$$

Where, A_b and E_b represent the cross-sectional area and modulus of elasticity, respectively.

Figure 6 illustrates the variance in lap shear-strength of joints with loading rate. It was witnessed that the increase in rate of loading causes increase in the shear-strength of the joint. Enhancement of shear-strength at a higher value of loading is not significant compared to the increase in shear-strength from static load to high load. A similar trend of variation in the dynamic strength of steel joints is reported in the literature [2, 3].

The comparative shear-strength of the lap joints under different loading conditions is summarised in table 1. At high loading rates, the shear-strength was enhanced by 2.5 to 6.0 times over the static loading. Reinforcement of the spherical shape of nano-alumina offered better properties than the rod shape of nano-alumina.

It is postulated that monomer molecules surrounded the nano-alumina and developed mechanical bonding and interlocking. When the curing agent was mixed in resin, the chemical bonding (van der Waals) between the nano-alumina and monomer was activated. The nano-alumina also filled the voids and microcracks in the epoxy matrix. The inclusion of nano-alumina into resin increased the viscosity of epoxy adhe-

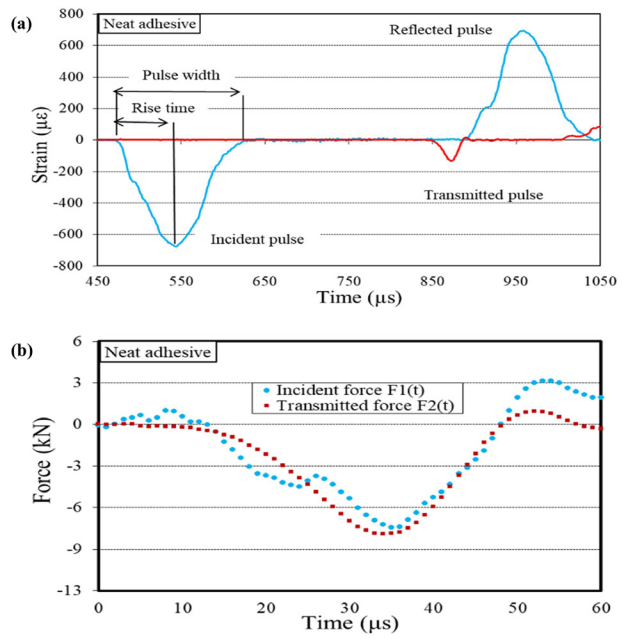

Figure 5: (a) Typical strain history and **(b)** Dynamic force profile.

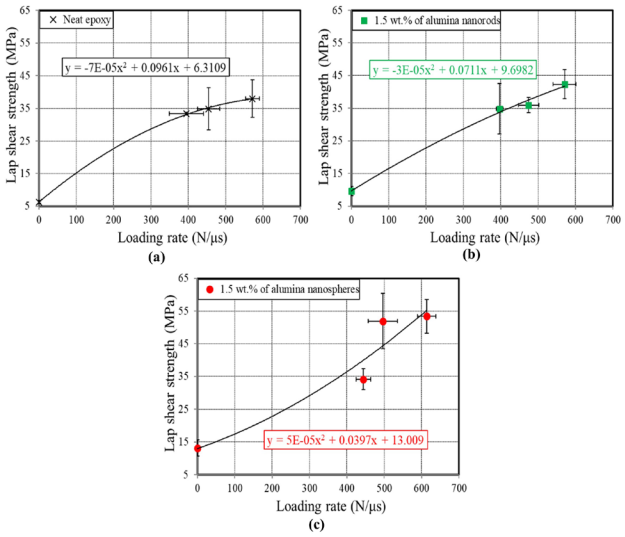

Figure 6: Variation of lap shear-strength with loading rates.

Table 1: Comparison of shear-strength under static and high loading of joints.

Adhesives	Static Shear-strength (MPa)	Dynamic properties		% increase over static strength
		Loading rate (N/μs)	Shear-strength (MPa)	
Neat (base) epoxy	6.3	394	33.36	430
		454	34.86	453
		571	37.97	503
Epoxy with 1.5 wt.% of rod nano-Al_2O_3	9.64	444	42.33	159
		496	35.95	294
		613	34.82	305
Epoxy with 1.5 wt.% of sphere nano-Al_2O_3	13.18	396	53.37	261
		474	51.92	273
		570	34.14	339

sives due to their molecular immobility. So, the elastic modulus of bulk epoxy/nano-alumina adhesive was increased. Fracture mechanisms (crack bridging, crack blunting, crack deflection, and crack pinning) are activated at the time of failure of joints.

Lap shear-strength of joints diminished at higher content of nano-Al_2O_3 (2.0 wt.% of nano-rods and nano-spheres). It is postulated that the nano-alumina created an agglomerate after filling the whole voids and microcracks in the matrix. Micrographs obtained from Transmission Electron Microscope (TEM) of bulk epoxy/nano-Al_2O_3 adhesive holding nano-rods and nano-spheres are represented in figure 7. It could be interpreted from figure 7, that beyond the optimum wt.% of the nano-Al_2O_3, the agglomerates are formed in a matrix. Because of agglomerates, the nano-Al_2O_3 do not form a mechanical interlocking and chemical bond suitably with epoxy monomers. The shear-strength of joints were higher under high rate of loading than that under static loading. The dislocation in nanocomposite adhesive obstructs the creation of dislocation. At high loading rates, the voids and microcracks present in the adhesive did not get time to realize these. Under high loading rate conditions, shear yielding, shear banding, and shear plugging mechanism are the main cause of increased strength of base adhesive [21]. Shear yielding denotes a process of plastic deformation without a significant change in volume under applied stress. Stress concentrations around the rigid particles change the uniaxial stress state to a triaxial stress state, which enables the matrix shear yielding. Strain-softening creates the formation of the shear band and continuously deformed locally at higher rates.

Illustrative bonded surfaces of joints fractured under static and high loading conditions are shown in figure 8. After analysis of all fractured surfaces, both cohesive and interfacial failure were present.

Conclusions

Epoxy/nano-Al_2O_3 adhesives were prepared by reinforcing the 0.5, 1.0, 1.5, and 2.0 wt.% of nano-Al_2O_3 rods and nano-Al_2O_3 spheres using the *in situ* polymerization method. The following facts are concluded from the present work.

- Lap shear-strength of single-lap steel joints under static loading was investigated by adding 0.5, 1.0, 1.5, and 2.0 wt.% of rod and sphere nano-Al_2O_3 in the epoxy adhesive. Whereas the maximum shear-strength under static loading was obtained for adhesive holding 1.5 wt.% of spherical nano- Al_2O_3.

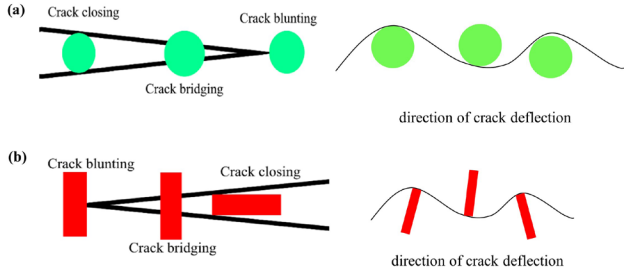

Figure 7: Schematic representation of fracture mechanism in epoxy/nano-alumina adhesive.

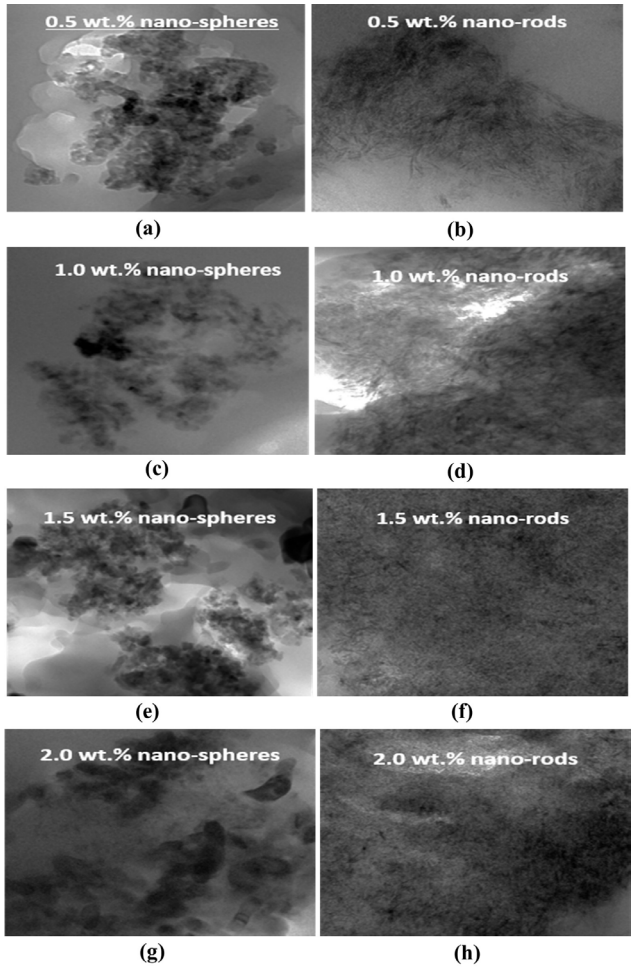

Figure 8: TEM micrograph images of bulk epoxy/nano-Al_2O_3.

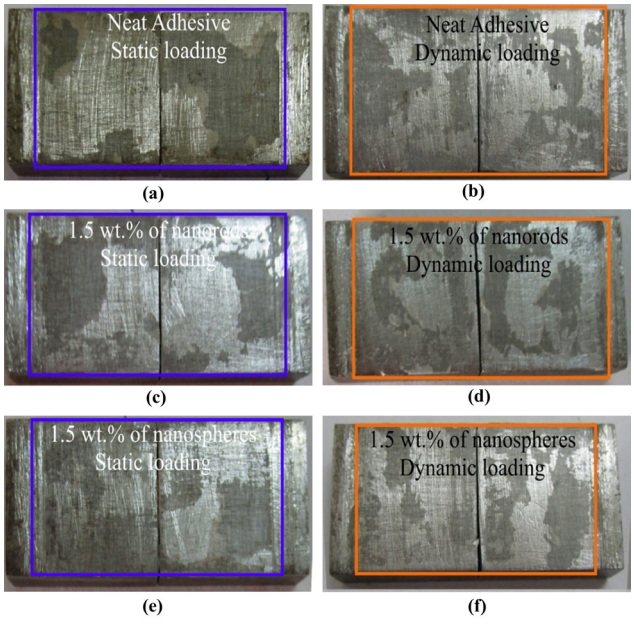

Figure 9: Illustrative bonded surfaces of joints fractured under static and dynamic.

- Shear-strength of epoxy/nano-Al_2O_3 adhesive improved with the rise of loading rate on joints. However, the increment in shear-strength among high loading rates

was not significant compared to the increase from static loading.

- Shear-strength of joints under increased loading conditions was investigated at ideal wt.% (1.5 wt.%) of nano-alumina obtained for static strength. The lap shear-strength at high loading rates was obtained 2.5 to 6.0 times higher over the static loading. Spherical nano-alumina provided a better advantage compared to rod alumina.

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Conflict of Interest

The authors confirm that there is no conflict of interests to report.

Credit Author Statement

Sunil Kumar Gupta: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft preparation; Dharmendra Kumar Shukla: Resources, Supervision; Swati Gupta: Writing - review and editing. All the authors read and approved the manuscript.

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