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Nano-silika ve GNP Hibrit Nanoparçacık Takviyeli Tek Bindirmeli Bağlantıların Kesme ve Kırılma Özellikleri

Özkan ÖZBEK*

Öne Çıkanlar:
- Yapıştırıcı ile birleştirilmiş bağlantılarda hibrit nanoparçacık kullanımı
- Hibrit nanoparçacıkların kayma dayanımına etkileri
- Nanoparçacıkların kırılma mekanizmalarına etkileri

Anahtar Kelimeler:
- Nano-silika
- GNP
- SLJ
- Kayma
- Kırılma

ÖZET:

Mevcut çalışmada, hibrit nanoparçacıkların, alüminyum altlıklar kullanılarak bağlanmış tek bindirmeli bağlantıların (SLJ) kayma ve kırılma davranışları üzerindeki etkileri araştırıldı. Bu amaçla, Araldite 2014-2 epoksi bazlı yapıştırıcıda dolgu malzemesi olarak nano-silika ve nano grafen (GNP) parçacıkları kullanılmıştır. Yedi farklı konfigürasyonda hazırlanan SLJ numuneleri bindirme kesme testine tabi tutulmuştur. Ek olarak, nanoparçacık ilavesinin bağlantıların kırılma özelliklerine etkisini anlamak için numunelerin hasarlı yüzeylerinden alınan makro ve SEM görüntüleri incelenmiştir. Deneysel bulgular ister tek ister hibrit olsun, tüm nanoparçacık katkılı numunelerin, saf olanlara kıyasla kayma mukavemetinde dikkate değer iyileşmeler sergilediğini göstermiştir. Maksimum iyileştirmeler, ağırlıkça %1 nano-silika ve ağırlıkça %0,5 GNP içeren H2 örneğinden elde edilmiştir. Maksimum kayma dayanımı saf numunelere (4,35 MPa) göre %213 daha yüksek olarak 13,62 MPa görülmüştür. Çatlak sapması, çatlak köprüleme ve boşluk oluşumu gibi bazı toklaştırma mekanizmalarının numunelerin iyileştirilmesinde kilit rol oynadığı belirlenmiştir. Bununla birlikte, H4 (ağırlıkça %1,5 nano-silika + ağırlıkça %1 GNP) gibi daha yüksek miktarlarda nanoparçacık eklenmesi, topaklanmaların neden olduğu malzeme bozulması nedeniyle maksimuma kıyasla kayma mukavemetinde düşüş göstermiştir. Sonuç olarak, nano-silika ve GNP parçacıkları, adhezif bağlantılarda sinerjik etki sergileyerek birlikte kullanılabileceğini kanıtlamıştır.

Shear and Fracture Characteristics of Nano-silica and GNP Hybrid Nanoparticle Reinforced Single Lap Joints

Highlights:
- Hybrid nanoparticle use in adhesive bonded joints
- Effects of hybrid nanoparticles on shear strength
- Effects of nanoparticles on fracture mechanisms

Keywords:
- Nano-silica
- GNP
- SLJ
- Shear
- Fracture

ABSTRACT:

In the current study, the effects of hybrid nanoparticles on the shear and fracture behaviours of adhesively bonded single lap joints (SLJs) using Aluminum substrates were investigated. To this aim, nano-silica and graphene nanoplatelet (GNP) particles were used as filler materials in Araldite 2014-2 epoxy-based adhesive. The SLJ samples prepared at seven different configurations were subjected to lap shear tests. Additionally, macro and SEM views taken from damaged surfaces of the samples were examined to understand the influence of nanoparticle addition on the fracture characteristics of the joints. The experimental findings showed that all nanoparticle-doped samples, whether single or hybrid, exhibited remarkable improvements in shear strength compared to pure ones. The maximum improvements were obtained from the H2 sample having 1 wt.% nano-silica and 0.5 wt.% GNP. The maximum shear strength was 13.62 MPa which was 213% higher than pure samples (4.35 MPa). It was determined that some toughening mechanisms such as crack deviation, crack bridging and plastic void formations had a crucial role in the enhancements of the samples. However, higher amounts of nanoparticle inclusion such as H4 (1.5 wt.% nano-silica+1 wt.% GNP) showed a decrease in shear strength, compared to the maximum one, due to the material degradation caused by agglomerations. In conclusion, nano-silica and GNP particles proved they could be used together by exhibiting a synergetic effect in the adhesive joints.

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INTRODUCTION

There is a need to combine various components in high-tech engineering applications by applying to join techniques to create structures or systems. Joints are one of the most critical parts of the structure that might be exposed to much more stress concentration compared to other regions of bonded materials. Therefore, the joining process of the components is one of the most sensitive points when building the structure and is of great importance. The applications of welding, bolting, riveting, and adhesive bonding are seen as the most common joining techniques used in scientific studies and industrial applications (Kumar et al., 2021; Wang et al., 2022; Gamdani et al., 2022). Among them, the adhesive bonding technique is frequently preferred especially in the automotive and aerospace industries, with its superior aspects such as enabling uniform stress distribution, weight reduction, aesthetic appearance, ability to combine different materials, and eliminating possible chemical reactions by preventing direct contact of the bonded materials (Adin, 2013; Akpınar, 2013; Adin and Kılıçkap, 2021; Atahan and Apalak, 2022; Uzun and Akçadağ, 2022).

The adhesive bonding technique causes the bonding area to be weak since the adhesive has lower mechanical properties than the substrate materials (Alies et al., 2022). To address this issue, scientists have studied some techniques such as the use of nano/microparticles, applying pretreatment to the adhesive, and changing the chemical/physical structure of the adhesive, which will improve the mechanical performance of the adhesives by increasing the adhesion ability (Bjørgum et al., 2003; Cakir and Kinay, 2021; Adin and Adin, 2022; Soydan et al., 2019; Esendemir et al., 2020). Herein, the incorporation of nano- or micro-scale particles into the adhesive has been one of the most popular methods, and it is seen in the literature that this seriously affects the mechanical performance of adhesive joints (Ayatollahi et al., 2017; Kanar et al., 2018; Saraç et al., 2019; Ghadge et al., 2021; Özbek et al., 2022). Khoramishad and Hosseini Vafa (2018) performed a study on the influence of aligning the graphene oxide nanoplatelets (GONP) on the fracture behaviours of adhesive joints. Using a direct current electric field, randomly aligned GONPs were dispersed into UHU plus endfest 300 to bond Al T6-6061 substrates. While the samples with 0.3 wt.% randomly dispersed GONPs showed the maximum load with an increase of 92%, 0.1 wt.% aligned dispersed GONPs exhibited 148% better results compared to the unreinforced adhesive joints. It was reported that lower amounts of GONP with aligned dispersion can be more effective. Cakir and Kinay (2021) examined the nanoparticle effects on the adhesion performance of Al-GFRP dissimilar materials bonded by SLJs. They dispersed the nanoparticles which used MWCNT, nano-silica, and nano clay as filler materials at various amounts into the Araldite 2014 adhesive. The best improvements were obtained from the 0.5 wt.% MWCNT doped samples as 62% compared to pure one. Also, 1.5 wt.% for both nano-silica (43.3%) and nano clay (37.8%) exhibited the highest values in their groups. Soltannia and Taheri (2022) investigated the effects of carbon nanotubes (CNTs), graphitized carbon nanofibers (CNFs), and graphene nanoplatelets (GNPs) on the adhesively bonded SLJs subjected to static, quasi-static, and impact loadings. Graphite/epoxy and glass/epoxy composite laminates were used as substrate materials. It was reported that GNP-reinforced SLJs had the highest results while all nanoparticle dispersions led to improvements compared to neat samples. NajiMehr et al. (2022) studied the influences of graphene nanoplatelet (GNP) and multi-walled carbon nanotubes (MWCNT) on the residual strength of SLJs exposed to fatigue loading. They used the nanoparticle amounts for 0.2%, 0.5%, 1%, and 2% by weight. It was reported that GNP addition exhibited the highest fatigue endurance compared to pure samples. They stated that the nanoparticle-reinforced samples showed remarkable improvements due to the formation of toughening mechanisms such as bridging, pull-out, crack deviation and crack arrest.

The crack propagation that occurred in the bonding region under loading can be tried to be delayed or stopped by incorporating nanoparticles into the adhesive resulting in increases in the strength of the material. In this context, nanoparticles have a direct effect on the fracture behaviour of the material by exhibiting some toughening mechanisms such as crack deviation, crack bridging, plastic voids, pinning, pull out, and branching with the effect of their structural forms (Çakır and Özbek, 2022). It has been clearly stated that the use of many nanoparticles leading to the formation of these mechanisms improved the material characteristics (Quan et al., 2018). Abbasi et al. (2021) investigated the effect of the mixture of silica nanoparticles (SNP), waste tire powder modified by acrylamide, and polyethylene terephthalate (PET) on the mechanical, and thermal stability behaviours of carbon/epoxy fibre-steel bonded joints. The best improvements according to the lap shear tests were achieved from the sample containing 10 wt.% modified tire powder-PET blend and 0.5 wt.% SNPs compared to neat samples. It was stated that the SNP exhibiting the fracture mechanisms such as debonding and plastic-void growth contributed to the material toughness. Gupta et al. (2021) examined the influence of nano alumina on the shear and fracture characteristics of aluminium joints. Alumina nanospheres and alumina nanorods with 0.5, 1.0, 1.5, and 2.0 wt.% were used as filler material in the epoxy adhesive. Maximum values in lap shear strength were obtained from the samples having 1.5 wt.% of nanospheres and 1.0 wt.% of nanorods. The higher strength of the joint was attributed to the efficient stress transfer between nano alumina and epoxy adhesive due to the formation of crack pinning and crack bridging toughening mechanisms.

Recently, scientists have been investigating the effects of two or more nanoparticle additions on the mechanical or fracture behaviour of materials, rather than using a single nanoparticle. The addition of hybrid nanoparticles to epoxy-based materials can provide much better results than the use of single nanoparticles by creating a synergetic effect and compensating for the adverse effects of the nanoparticles used. As in many areas, the hybridization of nanoparticles has begun to draw great attention in adhesive bonding studies due to its significant potential in tailoring the mechanical and physical properties of the adhesives (Özbek et al., 2022; Zamani et al., 2022). Razavi et al. (2018) studied the effects of hybrid nanoparticles on the average shear strength and elongation at break characteristics of Al-Al substrates bonded by SLJ. Equal amounts of silica nanoparticles (SNP) and MWCNT (total 0.2%, 0.5%, and 0.8% by weight) were used as filler materials and dispersed into UHU plus Endfest 300 adhesives. It was seen that 28% and 36% improvements in shear strength and elongation, respectively, were achieved from the samples having 0.8 wt.% nanoparticles (0.4% SNP+0.4% MWCNT). They stated that effective mechanisms such as plastic void growth and crack deviation directly contributed to better material properties. Rao et al. (2020) investigated the MWCNT, GNP, and their hybrids on the shear properties of the adhesively bonded joints. Carbon fiber-reinforced composites as substrate materials were bonded by epoxy adhesive. The synergy effect was seen from the 0.75 wt.% MWCNT/GNP hybrid nanoparticle reinforced samples showed 36.6% and 33.2% improvements in shear strength and elongation at break, respectively, compared with pure adhesive. They observed that the formation of crack deflection and crack pinning mechanisms showed a significant effect on the experimental results.

The current study aims to investigate the effects of nanoparticle hybridization on single-lap joints (SLJs). The novelty of this work is to examine the Nano silica and GNP hybrid effect on the lap shear strength and fracture characterization of adhesive joints of Al-Al substrates. Nano silica with a spherical form and higher ductility is small-size, cheap, and easy to access. On the other hand, GNP with a plate form is a 2-dimensional carbon structure, with expensive and high-strength particles. For this purpose, various amounts of combinations of nano-silica particles, which are cheaper and accessible in the market, and high-strength graphene particles, which are extremely popular among scientists in recent years, are added to Araldite 2014-2 epoxy-based commercial adhesive. The effects of hybrid nanoparticle reinforcements on shear properties were determined by applying lap shear experiments to the samples. In addition, the surfaces of the damaged samples were examined by scanning electron microscopy (SEM) and their fracture behaviours were analyzed to understand the hybridization effect on failure characteristics.

MATERIALS AND METHODS

Materials

In the present study, aluminium 2024 T3 (Al) sheets with 2 mm thickness, procured from Seykoç Aluminum, Turkey, are used as substrate materials. To bond substrates, Araldite 2014-2 epoxy-based commercial adhesive supplied from Huntsman Advanced Materials Americas LLC, Canada, was preferred due to its advantages such as its popularity in adhesive joints good chemical resistance, and high-strength two-component adhesive. The mechanical features of the 2024 T3 Aluminum substrates obtained from the company and Araldite 2014-2 according to ISO 527 were given in Table 1.

Table 1. The mechanical features of Al substrates and Araldite 2014-2 adhesive

Materials	Density (g cm^{-3})	Yield Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)
Al 2024 T3	2.77	340	475	68
Araldite 2014-2	1.60	-	30	3.1

Nano-silica (Graphene Chemical Industries Co. Ltd., Turkey) and graphene nanoplatelet (Nanografi Nanotechnology A.S., Turkey) particles were used as additives for dispersion into Araldite 2014-2. Nano silica having a purity of 99.5% was chosen as the main additive and added more to the adhesive. The reason behind this was to keep the cost low. However, GNP with 99.9% purity was added to the adhesive in lower amounts compared to nano-silica to provide higher mechanical characteristics. The physical properties of nano-silica and GNP particles are given in Table 2.

Table 2. The physical properties of nano-sized additives

Nanoparticle	Density (g /cm^3)	Surface Area (m^2 /g)	Diameter (µm)	Thickness (nm)	Particle Size (nm)
Nano-silica	0.05	300	-	-	15-35
GNP	2.4	170	7	5	3.1

Sample Preparation

The preparation of the samples can be divided into three stages; preliminary preparations, bonding application, and curing process. Firstly, the large Al plates were sliced as 100 mm in length and 25 mm in width. Then, the surfaces of Al to be bonded were abraded by 100-grit sandpaper to increase the adhesion capability between the adhesive and Al substrate. Using acetone (Merck 100014), the sanded surfaces were purified from physical and chemical pollutants. In the second stage, the Araldite 2014-2 adhesive and acetone in a beaker were mixed at an equal weight ratio (1:1) to reduce adhesive viscosity. Then, nano-silica and GNP particles were added to the mixture in different amounts. The naming of the samples and the number of nanoparticles used in the adhesive were given in Table 3. After that, the high shear mixing process using a lightweight homogenizer (Isolab) at 8000 rpm for 60 min with an interval of 5 min was performed to provide a homogeneous nanoparticle distribution (Gültekin et al., 2016). The amount of acetone was frequently checked during the mixing to ensure acetone disappearance. Vacuum degassing was applied to the mixture to remove the remaining air bubbles and acetone. The SLJ process was performed on the Al-made mould as seen in Figure 1. The overlap area and bond line thickness are measured as 25 mm x 25 mm and 0.2 mm, respectively. In the last stage, to achieve initial curing, the samples in the mould which were closed by a suitable weight on the upper side were left at room temperature for 24 hours. The post-curing was performed at 40ºC for 16 hours according to the manufacturer's guide (Huntsman Advanced Materials Americas LLC, Canada). According to previous investigations (Cakir and Kinay, 2021; Çakır and Özbek, 2022), the nano-silica and GNP amounts in single nanoparticle reinforced joints were just selected as 1.5 wt.% and 3 wt.%, respectively, due to their maximum improvements achieved from these. The experimental flow is given in Figure 2.

Table 3. The naming and the content of the adhesive used in SLJs

Naming	Araldite 2014-2 (wt.%)	Nano-silica (wt.%)	GNP (wt.%)
Pure	100.00	0.00	0.00
Nano-silica	98.50	1.50	0.00
GNP	97.00	0.00	3.00
H1	99.00	0.67	0.33
H2	98.50	1.00	0.50
H3	98.00	1.50	0.50
H4	97.50	1.50	1.00

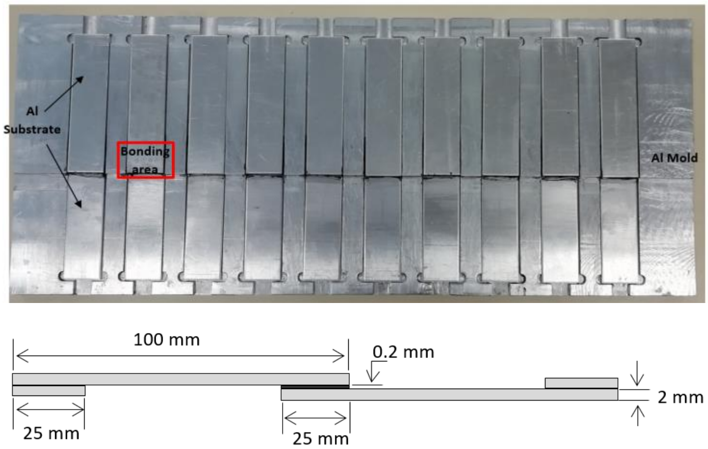


Figure 1. Single lap joints and sample geometry

Figure 2. The experimental flow of the samples

Lap Shear Test

The lap shear experiment which is the most widely used mechanical test to determine shear behaviours of SLJs was performed on a Shimadzu AG-X Series universal testing machine (Kyoto, Japan) having a 300 kN frame capacity according to ASTM D5868-01 (2008). The uniaxial tensile load with a crosshead speed of 1 mm min^{-1} was applied to samples until failure, as seen in Figure 3. The Al end tabs with 25 mm×25 mm dimensions were attached to samples to reduce the eccentricity of out-of-plane bending moments. The obtained load-displacement values were recorded by a data acquisition system and the maximum shear strength, max was calculated from the following equation;

$$\tau_{max} = F/(wd) \tag{1}$$

where F, w, and d denote the maximum load, width, and thickness of the samples. Five samples were tested at room temperature to ensure experimental reliability and the average of the values was evaluated in the results.

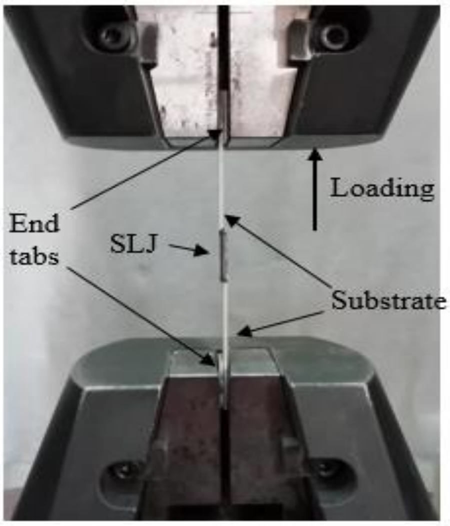


Figure 3. Lap shear test

RESULTS AND DISCUSSION

Lap Shear Test Results

The load-displacement diagrams obtained from the samples subjected to tensile loads are given in Figure 4. It was seen that all SLJ samples with nanoparticles, whether single or hybrid, exhibited higher load-bearing capability and elongation at break values. This can be attributed to the enhancements of interfacial interaction between nanoparticle and adhesive (Çakır and Özbek, 2022) which improves the material toughness due to better load-transferring capability. The fact that the nanoparticle additive to the adhesive increased the elongation at break indicated that the adhesive became more ductile. The best performance was achieved from the H2 samples which contain 1.0 wt.% nano-silica and 0.5 wt.% GNP while the lowest value was seen in the pure samples. Compared to pure samples, the improvements in elongations were found as 111%, 169%, and 346% for nano-silica, GNP, and H2 samples, respectively.

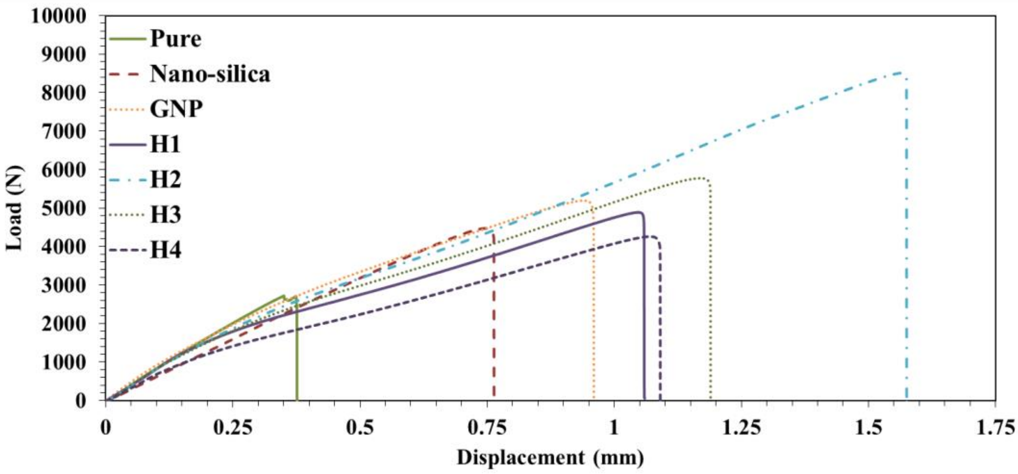


Figure 4. Load-displacement curves

However, a higher amount of nano-silica addition in hybrid samples (H3 – 1.5 wt.% nano-silica + 0.5 wt.% GNP) showed a decreasing load-carrying capacity compared to the maximum one (H2 sample). To fix this, an increase in GNP amount as seen in H4 samples (1.5 wt.% nano-silica + 1 wt.% GNP) resulted in even less. This can be explained by agglomeration formations that led to material degradations due to local stress concentrations. In the literature studies, it can be seen that an excessive amount of nanoparticle addition leading to agglomerations or exfoliations induced the material characteristics and resulted in decreases in experimental results (Bulut, 2017; Bozkurt et al., 2019).

The lap shear strength results of the SLJs with or without nanoparticles are presented in Figure 5. All samples including nanoparticle additives exhibited significant improvements compared to pure ones. The improvements in single nanoparticle reinforced SLJs were calculated as 64.5% and 91.0% for nano-silica and GNP, respectively. Additionally, H2 and H3 as hybrid nanoparticle doped samples exhibiting a synergetic effect showed a remarkable performance compared to others. The maximum shear strength of 13.62 MPa was achieved from the H2 sample which was 213.0%, 90.2%, and 63.9% higher than pure, nano-silica, and GNP joints, respectively. However, H4 samples including a higher amount of GNP than others showed a severe decrease due to excessive nanoparticle additions into the adhesive causing the agglomerations. The reduction was 50% in comparison with H2 samples. The fundamental reason for the agglomeration formations can be related to the attractive forces of the Van der Waals bonds and the large surface area of the nanoparticles, especially for GNP (Chatterjee et al., 2012). It was also thought that π–π bonds lead to the stacking of individual GNP layers (Chatterjee et al., 2012; Çakır and Özbek, 2022).

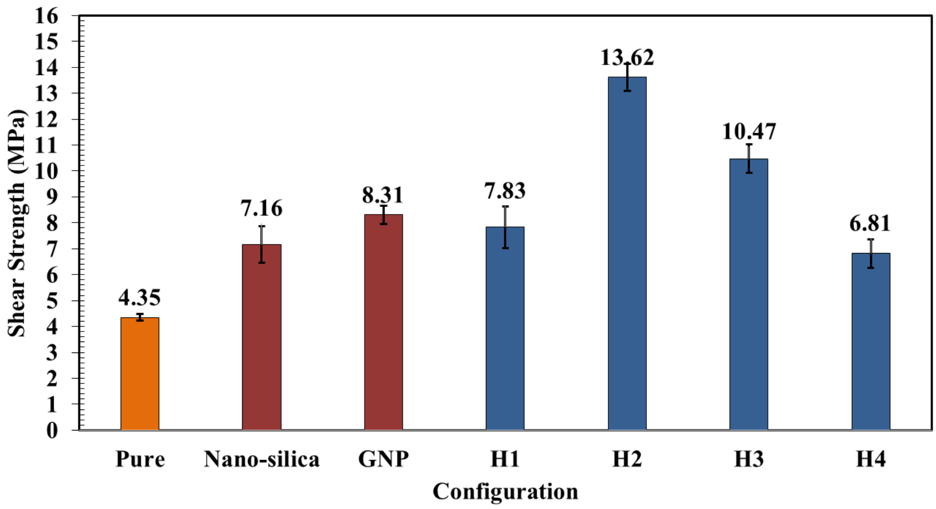


Figure 5. Shear strength

Damage Analysis

The damaged surfaces of the samples after lap shear experiments are seen in Figure 6. Typical failure patterns obtained from the metal substrates are known as adhesion, cohesion, and mixed-mode (adhesion+cohesion) according to EN-ISO 10365 (1995). Only the presence of remaining adhesive residue anywhere on a substrate indicates an adhesion failure has occurred at the interface between the adhesive and the adherend (substrate) (Bulut, 2017). In Figure 6, the presence of adhesive residue on only one of the substrates in the pure samples demonstrated that the deterioration was of the adhesive type. This confirmed that the adhesion between the aluminium adherent and the pure adhesive was poor as evidenced by the lap shear tests Cohesive failure means that the adhesion force to the substrate is greater than the intermolecular forces within the adhesive itself. The presence of an even layer of adhesive on substrates, as seen on the fracture surfaces of the GNP, H2, and H3 samples, indicated cohesive failure (Figure 6). In cohesive failure, the fracture does not occur until the load applied to the joints is higher than the internal cohesive strength of the adhesive, so it is the desired type of failure for adhesively bonded joints (Ahmadi, 2019). When the failure is mixed mode, adhesion and cohesion failures exist together, as seen on the fracture surfaces of nano-silica, H1, and H4 samples (Figure 6). In these samples, adhesive residues were observed both on only a single substrate (adhesion type) and matching surfaces of both substrates (cohesion type). In the mixed failure model, the strength of the joint is between the adhesion bond strength and the cohesion bond strength.

In general, adding nanoparticles to the adhesive caused the failure mode to change from adhesion to cohesion and thus increased the bond strength (Sadigh and Marami, 2016). This increase in bond strength is because the addition of nanoparticles activates different reinforcement mechanisms and changes the crack propagation and initiation behaviours in the adhesive layer, thus increasing energy absorption. The rougher fracture surfaces of the nanoparticle-added samples (Figure 6) and the increase in shear stresses (Figure 5) were evidence of the existence of complex reinforcing mechanisms. The fracture surfaces of the samples were analyzed by SEM images to investigate the reinforcing effect of nano-silica particles and GNPs and to identify the mechanisms involved in detail.

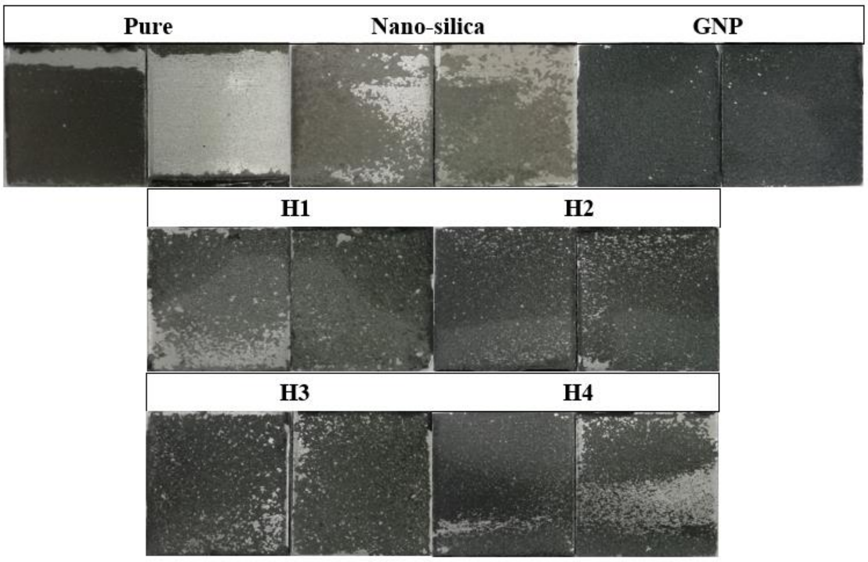


Figure 6. Damaged surfaces of the samples

The SEM views taken from the damaged surfaces of the samples are given in Figure 7. It can be said that the pure samples showed smooth surfaces without any prominent crack lines. This can be attributed to the weak adhesion capability of the joints due to the brittle nature of the adhesive could not start a deep crack initiation (Lee et al., 2008; Jojibabu et al., 2019). Only river-like lines were observed as rough regions. When the adhesive was reinforced with nanoparticles, the surfaces were rougher which shows the joints required higher forces. This can be related to the nanoparticle-doped samples exhibiting different fracture mechanisms showing better toughness and higher strength. Crack initiations and propagations were seen in samples with rougher surfaces than pure ones. It is seen that cracks deviated in nano-silica and hybrid nanoparticle-reinforced joints. Also, it is known that as the surface gets rough, more energy absorption was required to perform the sample fracture due to ductility increased (Sadigh and Marami, 2016). In the literature, several studies explained that more energy is required for crack propagation in the epoxy matrix filled with nanoparticles because the nanoparticles lead to the delay or stopping of the crack propagation (Ayatollahi et al., 2017; Khoramishad et al., 2017).

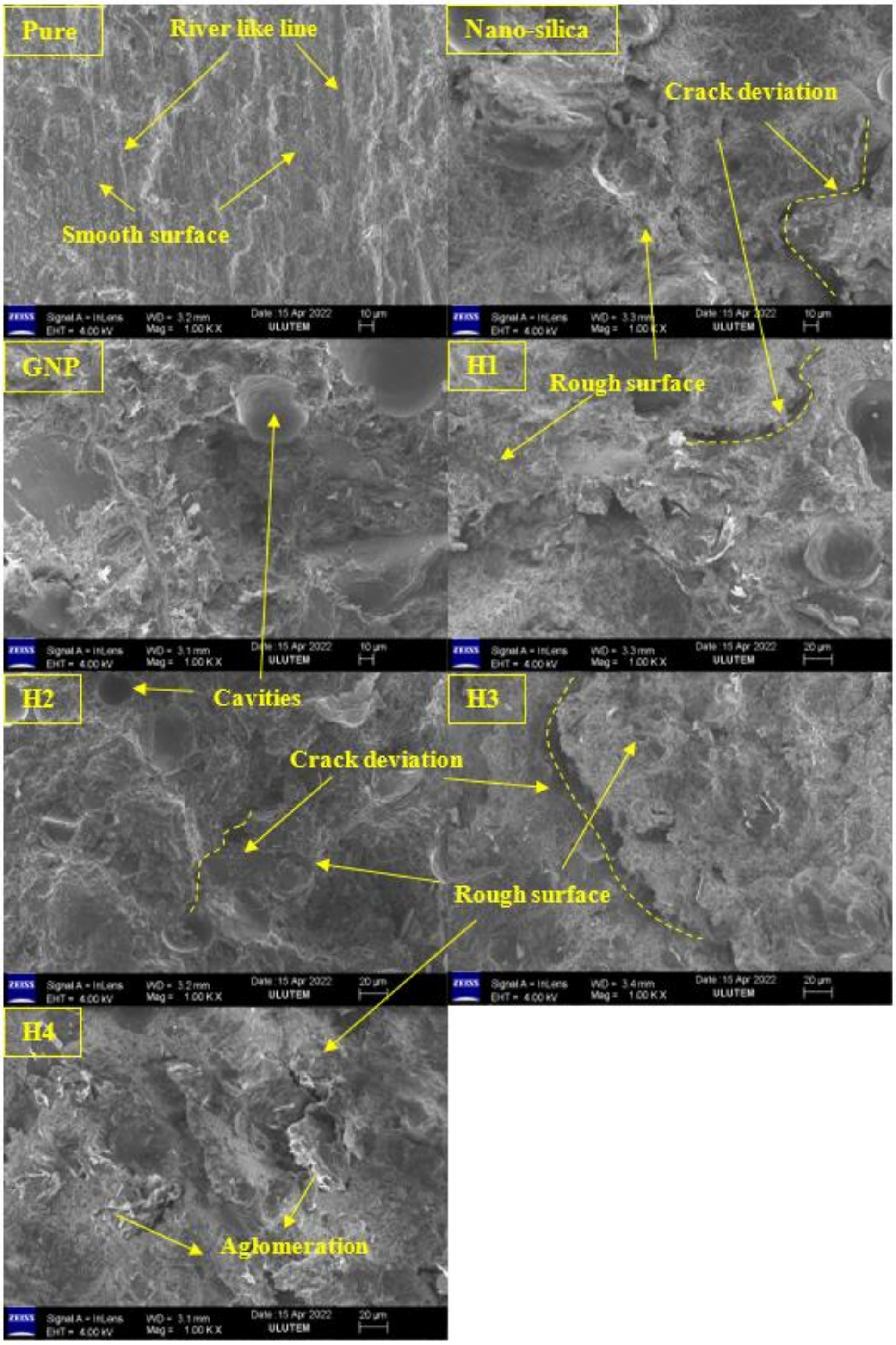
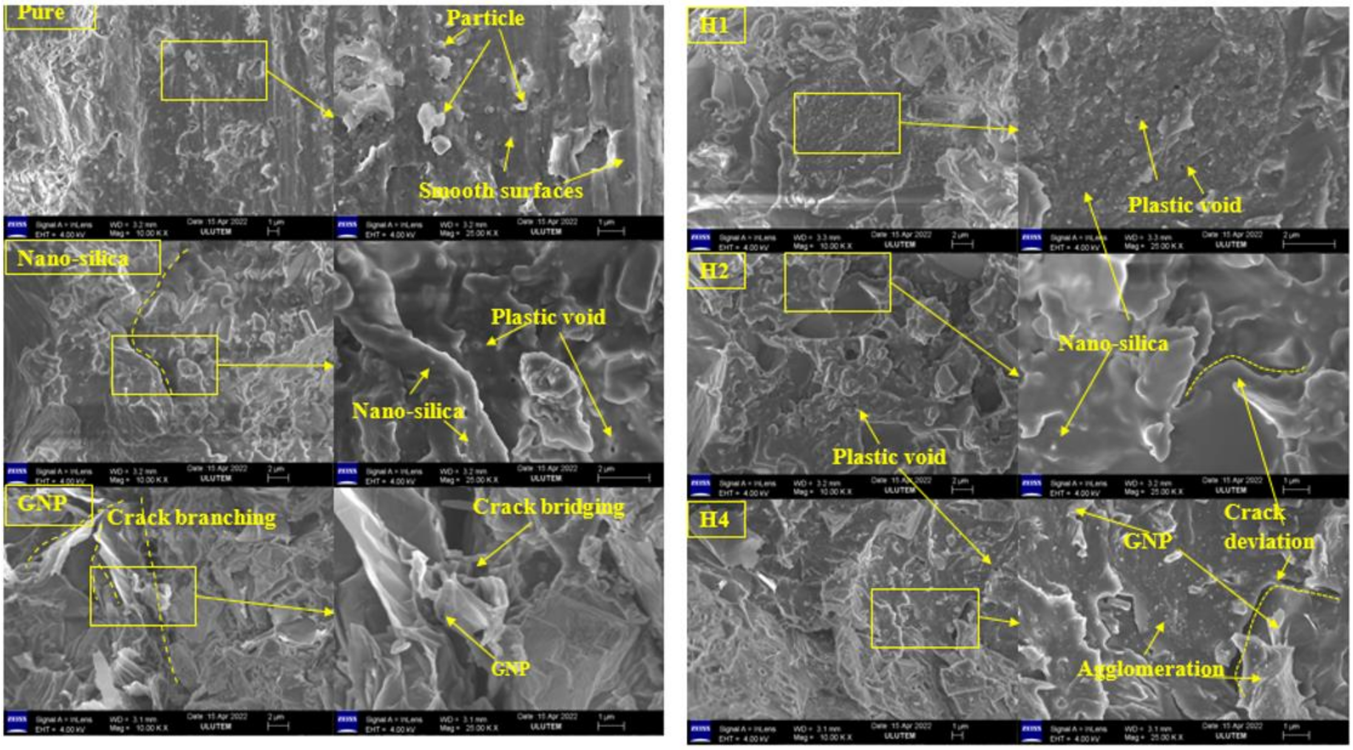


Figure 7. SEM views of the samples

The SEM images of the pure and single nanoparticle-reinforced samples (nano-silica and GNP) with high magnification are seen in Figure 8a. Araldite adhesive has some mineral particles of various dimensions and types. As seen in Figure 8a on the fracture surfaces of the pure samples, the stresses concentrated on the edges of these particles caused the initiation of cracks. The smoothness of the damaged surfaces was proof that the particles did not alter the brittle nature of the adhesive and had no effect on resisting crack propagation. However, the fracture surfaces of the nano-silica and GNP-doped samples were more complex and rough, as the nanoparticles enabled some mechanisms to increase the toughness of the adhesive. One of these effective mechanisms is plastic void growth seen in samples containing nano-silica particles (Figure 8a nano-silica view). These plastic void growths were formed due to the separation of nano-silica particles from the adhesive matrix. The increase in energy absorption for rupture due to the interfacial bonds of nano-silicas with the adhesive required more force to break the adhesion bonds, thus improving the shear strength of the adhesive bonds (Ayatollahi et al., 2017). Additionally, several toughening mechanisms on crack propagation were observed from the GNP-added samples. GNP particles tried to stop crack propagation, causing its delay. Due to GNPs having a large specific surface area, crack propagation deviated, and a crack branching mechanism occurred along with several layers of the GNPs. Also, the crack bridging mechanism was seen to delay the crack propagation and increase the fracture energy of the samples. Similar findings are seen in the literature studies (Ozcan et al., 2019; Wu et al., 2015; Silvestre et al., 2015).

The high-resolution SEM views of the hybrid nanoparticle-reinforced samples are presented in Figure 8b. Due to the nano-silica being the dominant nanoparticle in hybrid configurations, the formations of the plastic voids were observed in all samples. Generally, it was thought to be crack initiated and propagated until encountering a nano-sized additive. When nanoparticles behave as an obstacle, the crack needs more energy absorption and results in a delay or stop that increases the material strength. Alternatively, it develops a different mechanism known as a crack deviation that leads to a change in the crack growth path. This mechanism contributed to material toughness as seen in the H2 and H4 samples. Herein, nano-silica particles were detected on the GNP lamellae. The spherical nature of the nano-silica particles contributes to attracting large amounts of adhesive in all directions. Usually, GNP particles with a 2-dimensional structure cannot show much effect in the direction parallel to themselves. In contrast, the accumulation of nano-silica particles around them may have caused the formation of a 3-dimensional structure. This can try to prevent crack propagation in all directions. It is known in the literature that these 3-dimensional structures, for example, GNP and nano-silica, form lasagna-type structures (Agnello et al., 2017; Scaffaro and Maio, 2017).



a) b)

Figure 8. High-resolution SEM images of nanoparticle doped samples for; a) single nanoparticle, b) hybrid nanoparticle

This situation showed a synergetic effect, increased friction, required much more energy for crack propagation, and increased the ductility of the material. The experimental results pointed out this situation. The dense amount of nanoparticles has had various effects on crack propagation. Irregular nanoparticle distributions causing the agglomerations were detected in H4 samples. It was thought these regions behaving like local stress concentrations areas can be led to easy crack initiation and growth in the material due to non-uniformity (Zamani et al., 2022).

CONCLUSION

In this study, the effects of the hybridization of nano-silica and GNP nanoparticles on the shear and fracture behaviours of single lap joints were investigated. Aluminum 2024 T3 substrates were bonded by Araldite 2014-2 adhesive having various combinations of nanoparticles. Prepared samples were subjected to lap shear tests. Additionally, the fracture characteristics of the samples were analyzed via macro and SEM images taken from damaged surfaces. The obtained results can be summarized as follows;

- Nanoparticle dispersion into adhesive used in the bonding process had a significant impact on the shear and fracture behaviours of the joints.
- The samples with 1 wt.% nano-silica and 0.5 wt.% GNP particles exhibited the highest load-carrying capacity, elongations, and shear strength. Compared to pure samples, the maximum improvement in the shear strength of 213% was achieved.
- An excessive amount of nanoparticle addition leading to material degradation resulted in decreased experimental results due to the formation of agglomeration.
- The samples exhibiting cohesion failures (H2, H3, and GNP) showed better strength values than others (pure: adhesion, others: mixed-mode).
- Some toughening mechanisms contributing to the material characteristics were detected as plastic void formations, crack deviation and crack bridging.

In conclusion, the together contribution of nano-silica and GNP nanoparticles proved that the s hear characteristics of the SLJs can be considerably increased if they were used at specific values.

Conflict of Interest

The article author declares that there is no conflict of interest.

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