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Studies of Nanoscratching in the Aspect of Homogeneity of Adhesive Joints

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This paper presents the results of nanoscratch tests conducted on adhesive bond thickness, analyzed in terms of material property heterogeneity within adhesive bonds. Nanoscratch tests were performed on adhesive layers made from rigid and elastic adhesives with thicknesses of 0.05 mm and 0.1 mm, under constant load conditions. Penetration depth and residual depth results were analyzed for potential variations in hardness along the adhesive layer thickness. The findings clearly indicate some differences in the material properties of adhesive layers within bonded joints. These results can also be correlated with the phenomenon of apparent Young's modulus, which involves changes in modulus values across the adhesive bond thickness. These findings are crucial for understanding phenomena affecting the constitution of adhesive joints, enabling enhancements in their reliability and durability.

Keywords: Adhesive joints, Nanoscratch, Homogeneity of adhesive joints, Adhesive joint properties

1 Introduction

Adhesive joints constitute an essential element of modern material joining technologies, finding wide application in the aerospace, automotive, construction, electronic, and many other industries [1,2]. They enable the joining of diverse materials, such as metals, polymers, composites, or ceramics, without the need for high temperatures or plastic deformation [3]. The key advantages of adhesive joints are the uniform distribution of stresses, reduction of structural weight, and the ability to join materials with different physicochemical properties. However, the mechanical properties of adhesive joints are complex and depend on many factors, such as the type of adhesive, curing conditions, substrate surface preparation, adhesive layer thickness, and chemical and physical interactions at the adhesive-adherend interface [4-5]. In engineering practice, understanding and controlling these factors is crucial to ensure the durability and reliability of joints. These phenomena lead to changes in mechanical properties across the thickness of the adhesive layer, which has significant consequences for the behavior of the adhesive joint under load [7]. Heterogeneity can cause local stress concentrations, crack initiation, and affect the stiffness and strength of the joint [5,6].

The phenomenon of the apparent Young's modulus refers to the observed increase in the adhesive's modulus of elasticity near the adhesive-adherend interface compared to the core of the adhesive layer [3,4]. This is an effect of structural and potentially chemical heterogeneity in the adhesive layer, resulting from the previously mentioned factors. The apparent Young's modulus is significant in the context of numerical modeling of adhesive joints because traditional models assuming homogeneity of the adhesive layer may lead to inaccurate predictions of joint behavior under load [1,4].

To accurately investigate the heterogeneity of mechanical properties in adhesive layers, it is necessary to employ methods with high spatial resolution. Traditional strength tests provide information on the average properties of the adhesive layer but do not allow for the assessment of local variations [4,7]. In this context, techniques such as nanoindentation and nanoscratch testing are extremely valuable. Nanoindentation involves pressing an indenter of specified geometry and material properties perpendicularly into the material's surface under controlled load and measuring displacement at nanoscale [10,11]. This allows for the determination of local hardness and modulus of elasticity values of the tested material [8,9,12]. Nanoscratch testing is a method involving dragging a stylus of defined geometry and material properties across the material's surface under constant or variable load, enabling the evaluation of scratch resistance and analysis of changes in mechanical properties along the surface. The nanoscratch method can be particularly useful in studying the heterogeneity of adhesive layers because it allows mapping of changes in mechanical properties across the thickness of the adhesive layer and analysis of scratch depth as a function of distance from the adhesive-adherent interface [13]. This method can indirectly detect local changes in Young's modulus by comparing penetration depth and residual depth, which allows for the assessment of the elastic and plastic response of the material.

In the scientific literature, numerous publications can be found concerning nanoindentation and nanoscratch testing, used for nanoscale evaluation of material properties. Kucharski et al. [14] investigated the phenomenon of decreasing nanohardness at very small indentation depths in copper single crystals. The authors discovered that at ultralow penetration depths, the measured hardness values decrease due to the indentation size effect and surface influence, highlighting the challenges associated with accurate measurement of mechanical properties at the nanoscale. The article by Kese, Li, and Bergman [15] examines the influence of residual stresses on the modulus of elasticity and hardness of soda-lime glass measured by nanoindentation. The authors stated that the presence of residual stresses significantly affects the measurement results, emphasizing the necessity to consider these stresses when interpreting nanoindentation data for brittle materials. The article by Bernaczyk and collaborators [16] concerns the study of characteristics of various adhesive joints using nanoindentation and computed tomography. The authors applied these methods to analyze the mechanical and structural properties of adhesive layers, which allowed for a better understanding of their behavior and optimization of bonding parameters. The article by J. Tomastik and R. Ctvrtlik [17] presents the application of nanoscratch testing as a tool for evaluating the cohesion and adhesion properties of thin layers and coatings. The authors analyze the methodology of nanoscratch testing and its effectiveness in characterizing the mechanical properties of thin films, emphasizing the significance of this technique in material research. Other recent research investigates the microhardness and nano-hardness of various composite coatings applied to an aluminum substrate. Through systematic testing and analysis, the authors provide insights into how these coatings improve the material's mechanical performance and durability. [18] The article by P. Klučiar et. al examines the nanoindentation properties of an Inconel 625 alloy weld overlay deposited on 16Mo3 steel. By analyzing hardness and elastic modulus, the authors reveal how the overlay enhances the mechanical performance of the base material [19]. The discussed studies demonstrate the versatility of the presented methods related to nanoindentation and nanoscratch testing.

The thickness of the adhesive layer is one of the key parameters affecting the mechanical properties of the joint. Thinner layers may exhibit higher shear strength but are simultaneously more sensitive to heterogeneities and defects [4,6]. The type of adhesive, especially its modulus of elasticity, also plays a significant role. Adhesives with a higher Young's modulus are generally stiffer, which affects the stiffness of the joint but may be less resistant to cracking. The scientific literature presents studies on the influence of adhesive layer thickness on the stiffness of the adhesive layer. In the context of adhesive layer heterogeneity, changes in thickness can affect the proportion of interfacial zones in the total thickness of the adhesive layer, which has consequences for the distribution of Young's modulus [6,15,20].

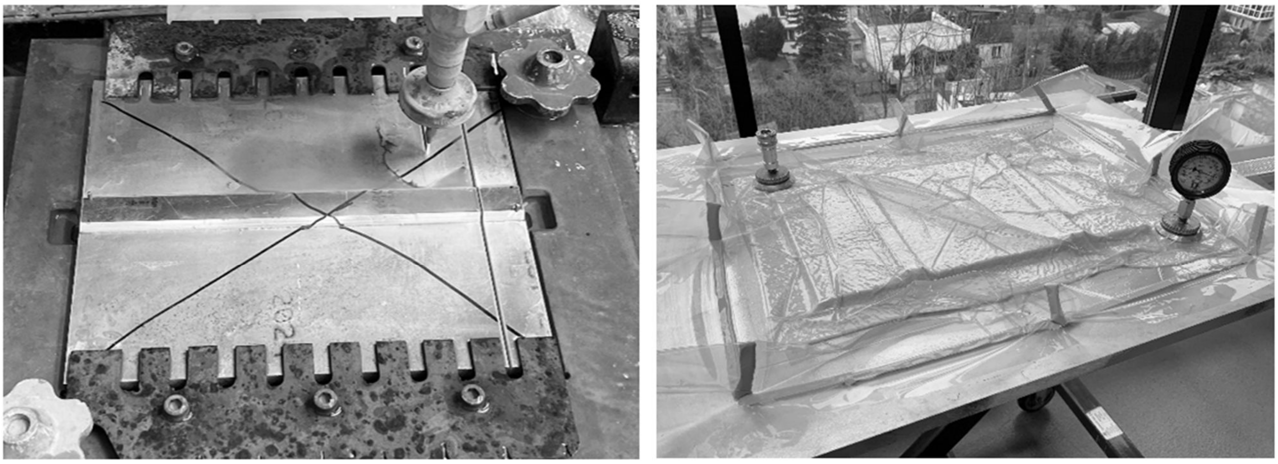
The aim of this study is to observe the heterogeneity of material properties in nanoscratch testing of adhesive layers across their thickness. In this case, changes in material properties will be identified through variations in the penetration depth of the indenter into the adhesive material. It is also essential for the conducted research to determine the influence of the type of adhesive (rigid vs. elastic) and the thickness of the adhesive layer on the distribution of Young's modulus.

2 Methods and Materials

For the study, two types of two-component resin based epoxy adhesives were used: E57/Z1 type: an adhesive with a high modulus of elasticity ranging from 1.7 GPa to 3 GPa, referred to in this article as "rigid". E57/PAC type: an adhesive with a lower modulus of elasticity ranging from 0.8 GPa to 1.4 GPa, referred to in this article as "elastic". The provided values of Young's modulus pertain to the adhesive material in the form of cast samples. These values can be significantly higher in the case of the adhesive within the joint, differing by as much as 60% or more [6]. E57 is a resin based on Bisphenol A and epichlorohydrin, combined with a polyester diluent. After curing, it exhibits high peel resistance. It is used in the preparation of adhesives for bonding metals, glass, ceramics, leather, as well as thermoset polymeric materials. The PAC hardener is a polyaminoamide (Polyaminoamide C) curing agent for epoxy resins, based on C18 unsaturated fatty acids, dimers, and polymeric reaction products with triethylenetetramine. It is a viscous, amber-colored liquid with a characteristic amine odor and relatively low reactivity. Epoxy resin formulations with the PAC hardener are applied in joining elements subjected to defor-mation. The PAC hardener increases the flexibility and impact strength of the adhesive composition. The Z-1 hardener [triethylenetetramine, polyethylenepolyamines, tetraethylenepentamine fraction, 1-(2-aminoethyl)-piperazine; 2-piperazin-1-ylethylamine, diethylenetriamine, 2-(2-aminoethylamino)-ethanol] is a transparent, liquid polyamide curing agent. It is primarily used for curing epoxy resins and their formulations. It is a homogeneous, clear, light-yellow liquid with a characteristic amine odor. Aluminum alloy EN-AW 2024-T3, commonly used in the aerospace industry due to its favorable strength-to-weight ratio, was used as the adherend material.

For the nanoscratch tests, four samples were prepared, two for each of the adhesive mixtures bonding the aluminum alloy EN AW-2024 T3, in two variants of adhesive bond thicknesses: 0.05 mm and 0.1 mm. The samples were in the form of double-lap joints, in accordance with the standard ASTM D3528, made into panels, from which individual samples for nanoscratch testing were cut. Aluminum alloy sheets were 4,58 mm and 9,16 mm thick. The set adhesive layer thicknesses were achieved by using spacers. Samples were cut using waterjet cutting. The sheet surfaces were cleaned with a cloth and a cleaner. To prepare the surfaces of the aluminum alloy sheets, P320 abrasive fleece was used; the surface was manually sanded to achieve a random distribution of irregularities. After sanding, the surface was cleaned with a cloth and twice with Loctite 7061 cleaner. Excess cleaner was wiped off with a cloth, and the sample was left to dry.

The selected adhesive composition was prepared with the utmost care. The components, weighed in predetermined proportions, were placed into a container where they were initially combined manually using a spatula. The epoxy resin E57 was mixed with hardener Z1 in a mass ratio of 12/100 and with hardener PAC in a mass ratio of 65/100, respectively. The adhesive compositions prepared in this way were then mechanically mixed using a disc stirrer for 3 minutes at a rotational speed of 400 rpm. During mixing, the direction of the stirrer rotation was changed six times. After mixing, the mixture was degassed for 5 minutes using a vacuum pump to remove air bubbles from the liquid adhesive. The adhesive mixture prepared in this way for each of the selected adhesives was ready for application. The mixture was applied to the cleaned surface of the sample using a spatula, evenly spreading the adhesive on both bonding surfaces. In the next step, the sheets were joined together, the joint was secured against displacement, and placed in a specially prepared vacuum bag, where a uniform pressure of 0.1 MPa was achieved through vacuum application. Due to the placement of spacers at three locations between the lap and the adherend, constant adhesive layer thicknesses were achieved. The spacers were precise steel shims with thicknesses of 0.05 mm and 0.1 mm. After joining, the samples were cured for 24 hours under constant environmental conditions: temperature of 18–20 °C and relative humidity of 38–40%. Then, after removing from the vacuum bag, they were seasoned for a minimum of 168 hours. Figure 1 shows an overview of the technology for making samples in the form of doubleoverlap joints, from which samples for the nanoscratch test were made: (a) cutting panels into individual samples, (b) curing adhesive joints in panel form in a vacuum bag.



a) b)

Fig. 1 *Technology for preparing panels of doubleoverlap specimens from which specimens were cut for nanoscratching tests*

After the seasoning period, specimens measuring 10 × 14 mm for nanoscratch testing were cut from the middle of the sheet using waterjet cutting. This cutting method minimizes the risk of joint destruction due to the absence of thermal effects in the cutting zone. The samples prepared in this way, with the surface exposed for testing, were placed in molds and embedded in resin. Samples with polished cross-sections of adhesive joints were prepared by initial grinding on grinding discs while applying intensive cooling. The surface preparation process continued using abrasive papers, starting with coarse-grit paper (180, 240) and proceeding to fine-grit papers (1000, 1200) for very precise processing. During grinding, conditions minimizing thermal effects on the adhesive layer were maintained. After grinding, the samples were mechanically polished on horizontally positioned rotating discs lined with felt and coated with an aqueous suspension of Al_2O_3. Polishing was carried out until a mirror-like, scratch-free surface was obtained. The finished sample was rinsed with water and ethyl alcohol, then dried in a stream of compressed air. Nanoscratch tests were conducted using an Ultra Nanoscratch tester manufactured by CSM Instruments, equipped with a spherical diamond stylus. The load resolution for the CSM Instruments nanoscratch tester is 0.15 μm, whereas depth resolution is 0.6 nm. Indenter positioning resolution in XY is 0.25 μm. On each sample, five passes of the stylus across the thickness of the adhesive layer were performed to average the obtained results. The nanoscratch test was conducted at a load force of 80 mN. The stylus translation speed was constant at 100 μm/min. The dependence of penetration depth on the length of the pass was recorded.

3 Results

Graphs of penetration depth versus traverse length indicate certain changes in material properties across the thickness of the adhesive layer. Changes in the material properties of the adhesive are associated with variations in the penetration depth of the adhesive layer by the indenter under a constant load force. In the interfacial zones directly adjacent to the adherend material, the scratch depth was smaller, which can be correlated with the occurrence of the apparent Young's modulus phenomenon. In the central part of the adhesive layer, the scratch depth increased, indicating lower hardness (stiffness) of the core of the adhesive joint.

Representative nanoscratch test curves for the studied adhesive layers are presented in Figures 3–6. The graph has a characteristic shape that includes penetration curve, stabilization, and exit from the adhesive joint. It can be observed that when the indenter approaches the adhesive-metal phase boundary, the scratch depth gradually decreases. Considering the author's previous studies, this behavior may be related to a local change in the properties of the adhesive layer in the interfacial zone. In analyzing the curve's trajectory, it is necessary to consider the nature of the test associated with the translational movement of the indenter and the material's elastic response during the test. Due to the relatively low test speed of 100 μm/min, it can be assumed that deformations in the material occurred immediately upon the application of force by the indenter. This means that the test is static rather than dynamic in nature. If we analyze the shape of the exit curve from the adhesive layer in terms of potential local property changes, a gradual rather than sudden exit of the indenter from the adhesive layer can be observed. Taking into account the author's previous studies, this may be correlated with the phenomenon of the apparent Young's modulus in adhesive layers [6]. It is worth noting that the indenter's radius of 2 μm should not affect the shape of the penetration curve caused by the indenter being repelled by the adherend material. Fig. 2 shows a microscopic image of the adhesive layer after the indenter's pass. In the image, one can observe the entry and exit zones of the nanoscratch, characteristic grooves along the sides of the scratch, and detached chips of the adherend material.

***Fig. 2** Microscopic photo of a nanoscratch on an adhesive bond made with 0.1 mm thick E57/PAC adhesive material*

Figures 3–6 present the curves showing the relationship between scratch depth and its length obtained in the nanoscratch test for rigid and elastic adhesives, with two adhesive layer thickness variants of 0.05 mm and 0.1 mm. The graphs include both the penetration depth (Pd) during the indenter's pass and the residual depth (Rd). It should be emphasized that the presented results are very high resolution. The analysis focused on the exit curves of the indenter from the adhesive layer, i.e., the curves on the right side of the graph. It can be observed that the exit curves for thinner adhesive layers start earlier, assume a steeper shape, and are capped with a characteristic offset indicating that in the zone directly adjacent to the bonded material, the adhesive exhibits higher hardness and consequently, higher stiffness. Similar conclusions can be drawn for rigid adhesives, except that the scratch depth is shallower, and the exit curve is more inclined compared to elastic adhesives. This is confirmed in nanoindentation studies, where differences in the Young's modulus values of "rigid" adhesives have a more linear character across the thickness of the adhesive layer.

The residual depth (Rd) in the nanoscratch test is the depth of permanent deformation remaining on the material's surface after the indenter has passed and the load has been removed. This means it measures the depth of the scratch that remains after the material has partially recovered its original shape due to elastic deformation. Residual depth is a key parameter for assessing a material's resistance to permanent, plastic deformation under mechanical load. Analyzing this parameter allows for the study of mechanical properties of materials at the nanoscale, such as hardness, scratch resistance, or coating adhesion. For all tested adhesive layers, an elastic response of the material was observed after the indenter's pass. However, for the elastic adhesive, this response is much more irregular, sometimes associated with permanent plastic deformations. The effective scratch depth decreased. The shape of the curve on the side of the indenter's exit from the adhesive layer is again noteworthy. The adhesive layer deformed much more after the indenter's pass, which may indicate greater stiffness of the adhesive layer in the interfacial zone compared to the centre of the layer.

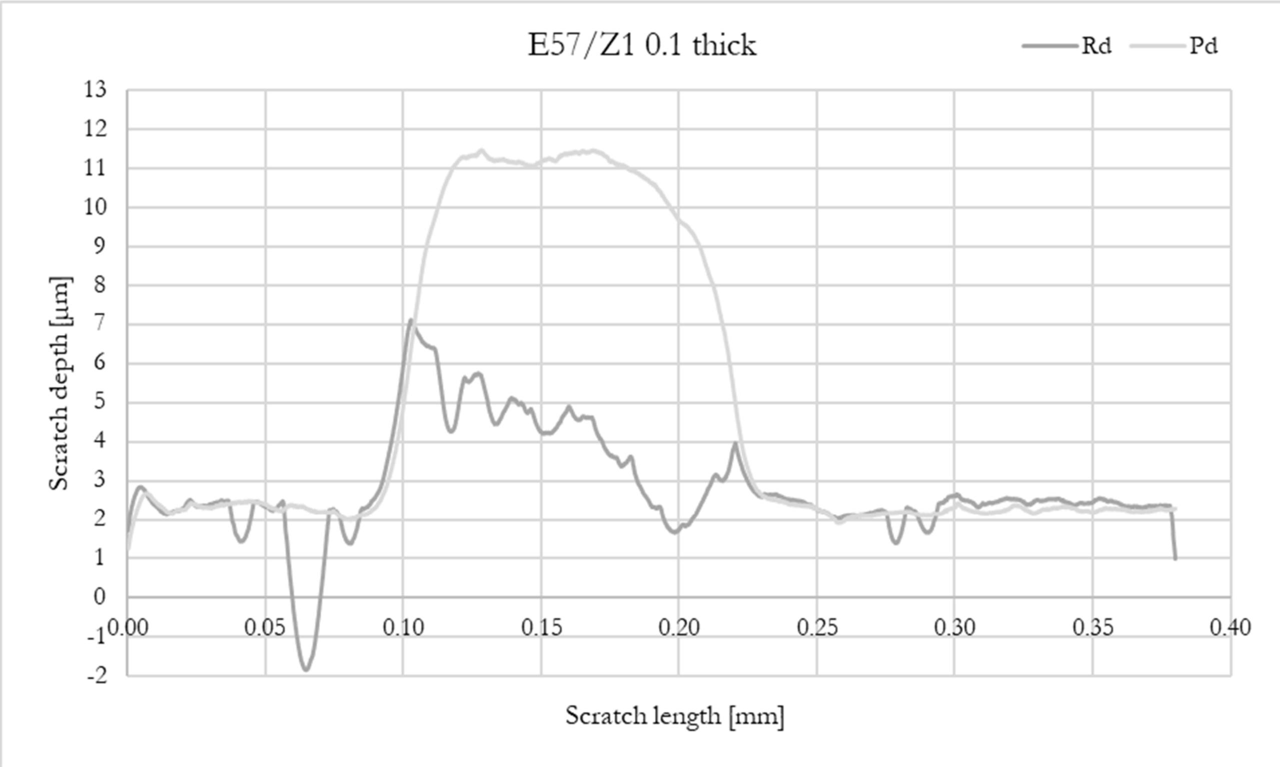


Fig. 3 *A graph of the nano-scratch test run for a 0.1 mm thick E57/Z1 adhesive bond, with the penetration depth curves Pd and residual depth curve Rd compared*

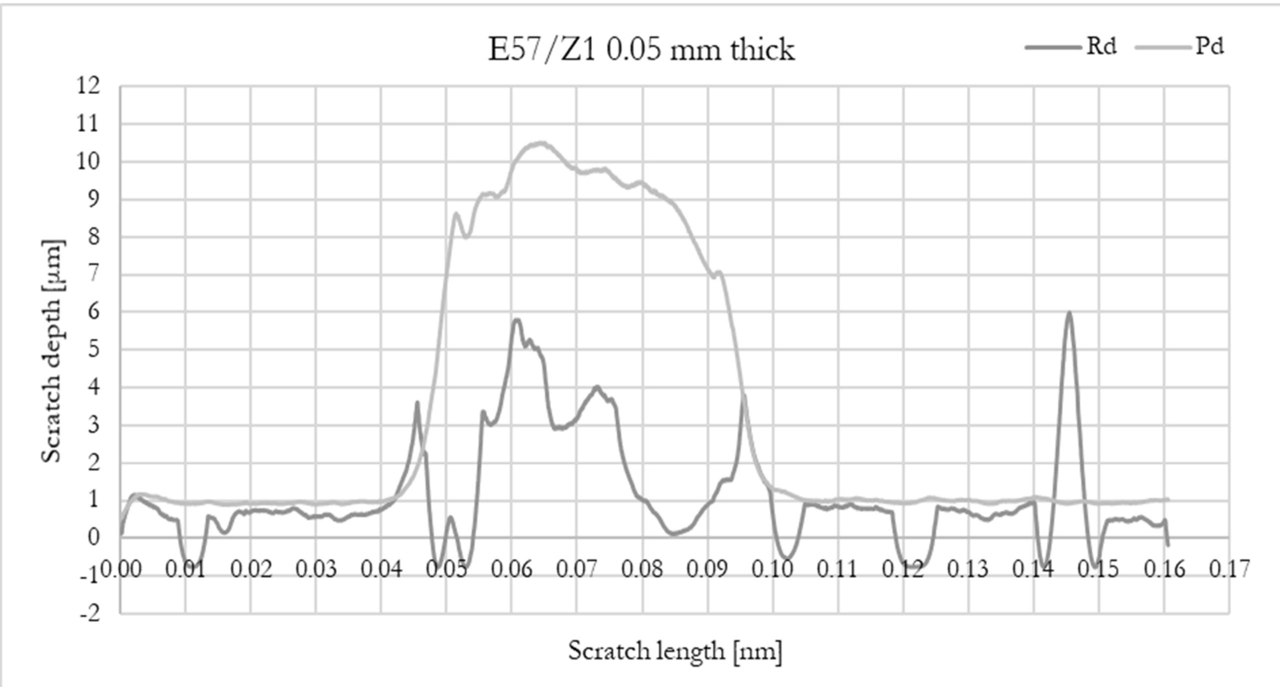


Fig. 4 *A graph of the nano-scratch test run for a 0.05 mm thick E57/Z1 adhesive bond, with the penetration depth curves Pd and residual depth curve Rd compared*

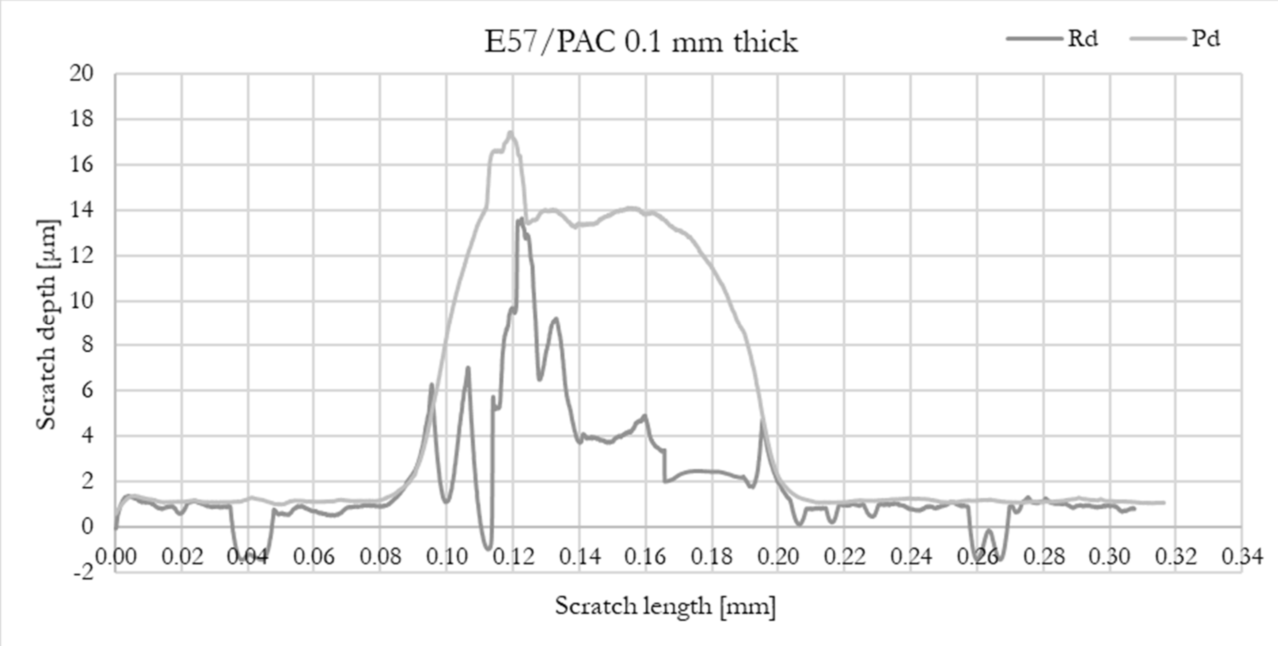


Fig. 5 *A graph of the nano-scratch test run for a 0.1 mm thick E57/PAC adhesive bond, with the penetration depth curves Pd and residual depth curve Rd compared*

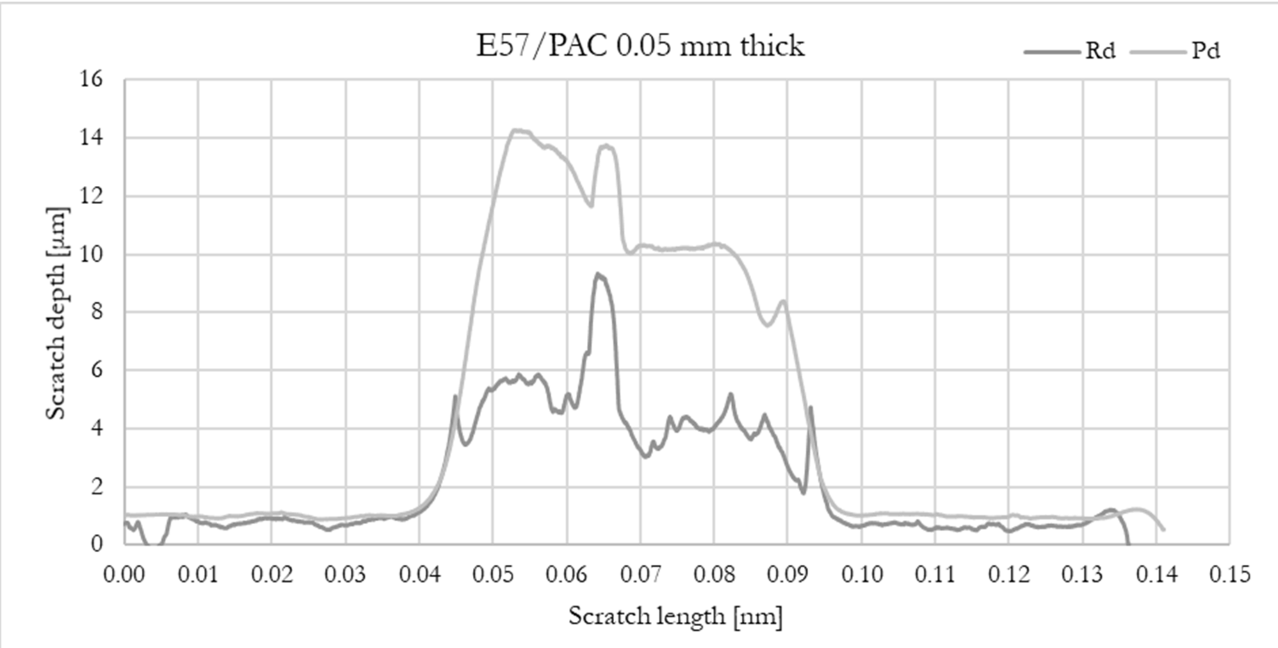


Fig. 6 *A graph of the nanoscratch test run for a 0.05 mm thick E57/PAC adhesive bond, with the penetration depth curve Pd and residual depth curve Rd compared*

In the presented graphs, peaks are visible near the phase boundary, which can be associated with remnants of material pushed by the indenter during the test and detaching from it upon crossing the metal-adhesive or adhesive-metal phase boundary. Therefore, in analyzing the curve profiles, it is necessary to consider the direction of the indenter's movement. Attention should be paid to the difference between the maximum scratch depth during the test, which for the E57/Z1 adhesive with an adhesive layer thickness of 0.1 mm averaged 12.1859 µm, and the maximum scratch depth after the indenter's pass and re-measurement, which is approximately 6.4122 µm. However, the most interesting is the area of the indenter's exit, where the elastic response of the adhesive material is much more intense. Considering the indenter's geometry and the original scratch profile, it can be concluded that the adhesive layer in the interfacial zone is characterized by greater stiffness than the zone in the centre of the adhesive layer. In the indenter's path at a distance of 0.16–0.20 mm, a gradual decrease in depth can be observed. At a distance of 0.19 mm, the penetration depth curve shows a depth of 11.1390 μm, while the value at the same distance on the residual depth graph is only 2.4586 μm. These values significantly indicate a difference in the stiffness of the adhesive in the zone closest to the bonded material compared to the zone in the centre of the adhesive layer. Similar behaviors were also observed in this zone for the elastic adhesive.

Table 1 summarizes the average maximum values of penetration depth and average maximum residual depth for the tested adhesives and adhesive layer thicknesses. Table 2 presents a comparison of average penetration depths (Pd) and average residual depths at characteristic distance of the adhesive layer in the interfacial zone - at a characteristic distance from the edge of the adhesive layer. For adhesive layers of 0.1 mm thickness, a characteristic distance in the interfacial zone, i.e., 0.19 mm, was chosen. For layers of 0.05 mm thickness, distances in the interfacial zone at 0.09 mm on the graph were selected. The selection of these points aims to confirm differences in the elastic response of the material in the adhesive layer. It can be observed that for thinner adhesive layers, the average maximum depth is smaller, which may indicate a local change in the material properties of the adhesive layer. The shorter penetration path should also be considered, which may affect the reduction of scratch depth.

Tab. 1 *Comparison of average maximum penetration depths Pd and average maximum residual depths Rd for the tested adhesive joints*

Adhesive material	Adhesive joint thickness [mm]	Average maximum penetration depth (Pd) [μm]	Standard deviation [μm]	Average maximum residual depth (Rd) [μm]	Standard deviation [μm]	Difference of average depth values (Pd-Rd) [μm]
E57/PAC	0.05	13.8244	0.5087	9.3655	0.3447	4.4589
	0.1	14.8474	0.6816	11.8249	0.7793	3.0225
E57/Z1	0.05	10.5150	0.4186	5.8768	0.2786	4.6382
	0.1	12.1859	0.7825	6.4122	0.4132	5.7738

Tab. 2 *Comparison of penetration depth Pd and residual depth Rd at characteristic distances in the wall zone of the adhesive joint*

Adhesive material	Adhesive joint thickness [mm]	Average penetration depth at characteristic distance (Pd) [μm]	Standard deviation [μm]	Average residual depth at characteristic distance (Rd) [μm]	Standard deviation [μm]	Difference of average depth values (Pd-Rd) [μm]
E57/PAC	0.05	7.6252	0.2806	2.2366	0.0823	5.3886
	0.1	8.2216	0.3775	2.4341	0.1604	5.7875
E57/Z1	0.05	7.1484	0.2846	0.9833	0.4661	6.1651
	0.1	11.1390	0.7825	0.2459	0.3132	8.6804

4 Discussion

The nanoscratch test allows for a quick assessment of the adhesive material's properties. Using this method, one can determine the scratch depth under a constant applied force. This method is often used to determine coating adhesion. However, its appropriate application and interpretation of obtained results can be an alternative to nanoindentation studies. Nanoindentation tests are used when precise determination of material properties is required, especially in the variant of testing with surface mapping.

Analyzing the obtained results in terms of the occurrence of the apparent Young's modulus phenomenon in adhesive layers, it can be stated that the nanoscratch curves, in a sense, confirm changes in the stiffness of the adhesive layer across its thickness. Furthermore, they indicate its heterogeneity. A smaller penetration depth was observed in the interfacial zones, which is associated with higher hardness or stiffness of the adhesive layer; this may result from stronger physicochemical interactions between the adhesive and the substrate and a higher degree of crosslinking in these areas. The local change in adhesive hardness within the joint, and consequently its stiffness, may be the result of the influence of very rigid aluminum alloy adherends, leading to an apparent change in hardness in the zone directly bonded with the adherend material. A very important aspect of the conducted research is the comparison of penetration depth with residual depth, associated with the material's elastic response after the removal of the force applied to the indenter. In each of the analyzed adhesives, especially in the case of rigid adhesive (E57/Z1), an intense material response was observed after the removal of the force. For rigid adhesives, the differences in depths between Pd and Rd are greater compared to elastic adhesives, which is consistent with expectations. Equally important is the comparison of depths at the characteristic distance, i.e., where a specific strengthening of the adhesive layer was expected, which should result in smaller penetration depths and a greater difference between Pd and Rd values, associated with an increased Young's modulus in this zone. Significantly greater differences in average penetration and residual depths were observed in the interfacial zone. These values are even greater for adhesive layers of smaller thickness, i.e., 0.05 mm, where greater strengthening of the adhesive layer was expected.

Rigid adhesives (E57/Z1) showed a smaller scratch depth compared to elastic adhesives (E57/PAC), which is consistent with expectations due to their higher modulus of elasticity. The higher modulus of elasticity of the rigid adhesive translates into greater resistance to stylus penetration. In contrast, elastic adhesives, due to their lower modulus of elasticity, are more susceptible to deformation under the stylus load, resulting in a greater scratch depth. Comparing the shape of the penetration depth graph for all tested adhesives, it can be observed that for rigid adhesives, it takes on a more uniform shape without sudden indentations into the material, unlike in the case of elastic adhesives, where sudden indentations into the material can be observed without a visible transition zone. This reflects the properties of elastic adhesives, which are characterized by a lower Young's modulus and according to the author's previous studies, exhibit more pronounced zoning compared to rigid adhesives, where the division into zones is less distinct.

The thickness of the adhesive layer has a significant impact on its mechanical properties. Thinner adhesive layers (0.05 mm) exhibited higher surface hardness than thicker layers (0.1 mm). This may result from the dominant influence of the interfacial zones on the entire volume of the thinner adhesive layer, causing greater homogeneity of mechanical properties. In thicker adhesive layers, the core of the layer has a greater contribution to the overall mechanical properties, making the effect of the apparent Young's modulus less pronounced.

The research presented in this article should be analyzed in the context of adhesive joint strength. Typically, the material within the adhesive bondline is assumed to be homogeneous, meaning that its properties do not vary across the thickness of the adhesive layer. Considering the findings presented herein, as well as the author's previous studies, it should be emphasized that assuming a homogeneous adhesive layer introduces a certain error. Literature studies indicate a general tendency for thinner adhesive layers to achieve higher joint strength compared to thicker ones. Relating these results to differences in nano-scratch depths and, consequently, the stiffness of the adhesive layer with respect to its thickness, one can observe a correlation between the higher stiffness of thinner adhesive layers and their enhanced strength. In the modeling of adhesive joints, accounting for variations in Young's modulus within the adhesive layer improves the accuracy of reproducing the joint's behavior under load. Such a modification of the material model, however, is usually not feasible using native functions of simulation software. It is necessary to employ user-defined functions through the incorporation of an external program that compiles variable fields. Moreover, the use of user-defined functions in modeling adhesive layers allows for the representation of their nonlinear behavior.

5 Conclusions

The conducted studies have shown that the occurrence of heterogeneity in the material properties of adhesive layers can be determined using the nanoscratch test. This test can be used to observe the consequences of the apparent Young's modulus phenomenon, involving local strengthening of the adhesive in the interfacial zones. Rigid adhesives are characterized by a smaller scratch depth compared to elastic adhesives, which results from their higher modulus of elasticity. The elastic response of the material after the removal of force is much more pronounced in the interfacial zone than in the centre of the adhesive layer for all tested adhesives, indicating the heterogeneity of the adhesive layer across its thickness. Thinner adhesive layers exhibit higher resistance to indenter penetration than thicker layers, which is related to the dominant influence of the interfacial zones on the entire thickness of the layer; simultaneously, the elastic response of the material in thinner layers is more intense.

The results of the research are significant, especially in the context of designing durable and reliable adhesive joints. Understanding the influence of adhesive layer heterogeneity on their mechanical properties allows for the optimization of bonding processes through control of adhesive layer thickness and selection of the appropriate type of adhesive. The application of the nanoscratch method in the study of adhesive layers can contribute to a better understanding of phenomena related to the formation of adhesive joints, which in turn allows for increased reliability and durability.

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