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Research Article

Investigation of failure loads of adhesive bonded and induction welded joints on similar and dissimilar substrates

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ABSTRACT

This study investigates the effect of adhesive bonding and induction welding on the maximum load of joints of Additive Manufacturing (AM) printed thermoplastic substrates with steel substrates. DINC75 was used as steel substrate and polylactic acid (PLA) as thermoplastic substrate. Fast-curing cyanoacrylate adhesive was used as adhesive. As the novelty of the study, there is a type of joint formed by induction welding of 3D printed substrates with steel has not been found in the literature. Single lap joint (SLJ) and double lap joint (DLJ) geometries were selected as joint geometries. The maximum load of joints was determined by applying tensile test to the joints. As a result, all the joints showed no adhesive failure and also the induction welded joints showed 27.51% and 65.49% increase in failure load compared to adhesive joints for SLJ and DLJ, respectively. The maximum load of joint of 9.40 kN was obtained for the DLJ geometry prepared by induction welding. Induction welding was found to be a good alternative to adhesive bonded joints.

1. Introduction

Adhesive bonding is a critical technique utilized in various fields such as dentistry, materials science, and engineering due to its ability to establish robust and enduring bonds between different materials. These joints offer several advantages over traditional bonding methods, including a more uniform stress distribution along the bonded area, leading to enhanced structural integrity and load-bearing capacity of Additively manufactured components [1]. Furthermore, these joints contribute to weight reduction in structures by eliminating the need for mechanical fasteners, such as rivets and bolts, thereby enhancing the overall efficiency of the bonded component [2]. The use PLA in AM has facilitated the creation of complex, customized structures with unique properties.

Zhang et al. [3] investigated surface modification approaches to enhance the lap shear strength of epoxy bonded joints and highlighted the significance of optimizing the crosslinking structures within the polymeric layer to augment the overall bond strength. This research emphasizes the crucial importance of surface treatments in achieving strong adhesive bonded joints in polymer additive manufacturing applications. Golewski et al. [4] conducted an empirical investigation on single lap hybrid joints composed of 3D printed polymer and aluminum substrates. They offered valuable perspectives on the mechanical behavior and performance of hybrid joints and stressed the significance of comprehending the interplay between diverse materials in adhesive bonded structures. Silva et al. [5] investigated the joining of additive manufacturing components via “mortise and tenon” joints, demonstrating the feasibility and deformation mechanics of this new joining process. By investigating the deformation mechanics of single lap joints in additive manufacturing, this study contributes to improving the design and fabrication of complex structures using adhesive bonded joints.

Induction welding of steel with thermoplastic materials is an advanced joining technique that has gained significant interest across various industries, particularly in aerospace and automotive applications. Two thermoplastic parts, called substrates, can be joined together using this method. This can be done with resistance welding, ultrasonic welding, and most importantly, induction welding [6,7]. Induction welding is recognized for its speed, cleanliness, and contact-free nature, reducing welding time and eliminating the need for mechanical fastening methods like rivets and bolts,

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thereby preventing weight increase in the final joint [8]. This technique has been acknowledged for its potential in cost reduction and environmental impact mitigation while maintaining joint quality at acceptable levels, making it a promising solution for various applications, including aerospace technologies [9]. Induction welding is particularly suitable for large-scale applications in industries like aerospace, where it is employed to efficiently and effectively join thermoplastic composite structures [10]. The automated nature of the technology and its ability to produce high-quality joints make it a preferred choice for welding steel with thermoplastic materials in various structural components. The process of induction welding is highly automated and suitable for long production runs, making it a preferred choice for welding steel pipes and other components in industrial settings [11]. Also, ongoing improvements in induction welding technology have worked on improving the mechanical performance of joints made of reinforced plastics. This shows that efforts are still being made to improve the quality and dependability of welded joints [12].

In the realm of thermoplastic composites, induction welding offers a rapid and reliable method for joining different materials, including metals like steel, to create robust and durable structures [13]. The precise control of through-thickness temperature distribution during induction welding of carbon composite aerospace parts showcases the precision and control achievable with this technique, ensuring uniform heating and high-quality joints [14]. Thorough research has contrasted induction welding for thermoplastic composites with other welding methods such as ultrasonic and resistance welding, emphasizing its distinct benefits and abilities in joining complex materials [15]. Additionally, the use of induction welding for repairing impacted thermoplastic composite laminates underscores its versatility and effectiveness in maintenance and repair applications [16]. Furthermore, researchers have explored the use of advanced techniques like material extrusion and friction stir welding to create single lap joints between polymers and metals [17,18]. These methods offer unique advantages in terms of joint strength and integrity, especially when joining dissimilar materials like polymer and aluminum alloy. By leveraging these innovative joining techniques, manufacturers can achieve robust and durable single lap joints in polymer additive manufacturing applications.

The utilization of induction welding in joining thermoplastic composites with steel has been extensively researched and developed. The utilization of stainless steel mesh as a susceptor in thermoplastic composite induction welding showcases the adaptability and efficiency of this method [19]. Induction welding for thermoplastic composite materials is commonly treated as a complex problem involving multiple physical factors. Researchers use finite element methods and process modeling to study and improve the performance and efficiency of this process [20]. Novel heating components, such as conductive films made of carbon nanofibers coated with metals like silver or nickel, have been created for use as heating elements in the induction welding of thermoplastic composites. This advancement significantly improves the capabilities and potential uses of this technology [21].

In conclusion, induction welding of steel with thermoplastic materials is a cutting-edge joining technique offering numerous advantages in terms of efficiency, reliability, and joint quality. The literature highlights the potential of induction welding in creating robust joints between thermoplastic composites and metals, especially in applications where weight reduction and structural integrity are critical, such as in the aerospace and automotive industries. However, previous studies have generally used either a conductive composite or a conductive part (susceptor) when induction welding a metal plate with a thermoplastic material. In this study, as different from the literature, steel and thermoplastic material were joined by adhesive bonding and induction welding method. DINC75 was used as steel substrate and 3D printed PLA was used as thermoplastic substrate. SLJ and DLJ geometries were selected and the effect of joining type on failure load was investigated. The maximum load of joint values was determined by uniaxial tensile test method.

2. Experimental Procedures

2.1 Materials

In this study, a series of controlled experiments were conducted to assess the impact of induction welding and adhesive bonding technology on the bond strength of joints. The dissimilar joints considered for this study are 3D printed and DIN C75 high-strength steel substrates. Material Extrusion technology and PLA thermoplastic filament (Porima industrial, Yalova, Turkey) were chosen as the material for the 3D printed substrates. 3D printing process was performed using a ZAXE X1 3D printer (ZAXE, Istanbul, Turkey) equipped with a 0.4 mm nozzle [22]. The printing parameters were set using the XDesktop slicing program based on the filament manufacturer’s data sheet. Bed and extrusion temperatures were 60°C and 210°C respectively [23], with on-edge orientation and tensile load direction [24]. The mechanical properties of PLA and DIN C75 are given in Table 1. A cyanoacrylate type adhesive manufactured by VODABOND (Taiwan) with fast-curing properties was used to produce the bonded joints. Furthermore, the adhesive was chosen as it is suitable for joining polymer materials with low surface energy and its fast-curing property is similar to the joint times produced by induction welding.

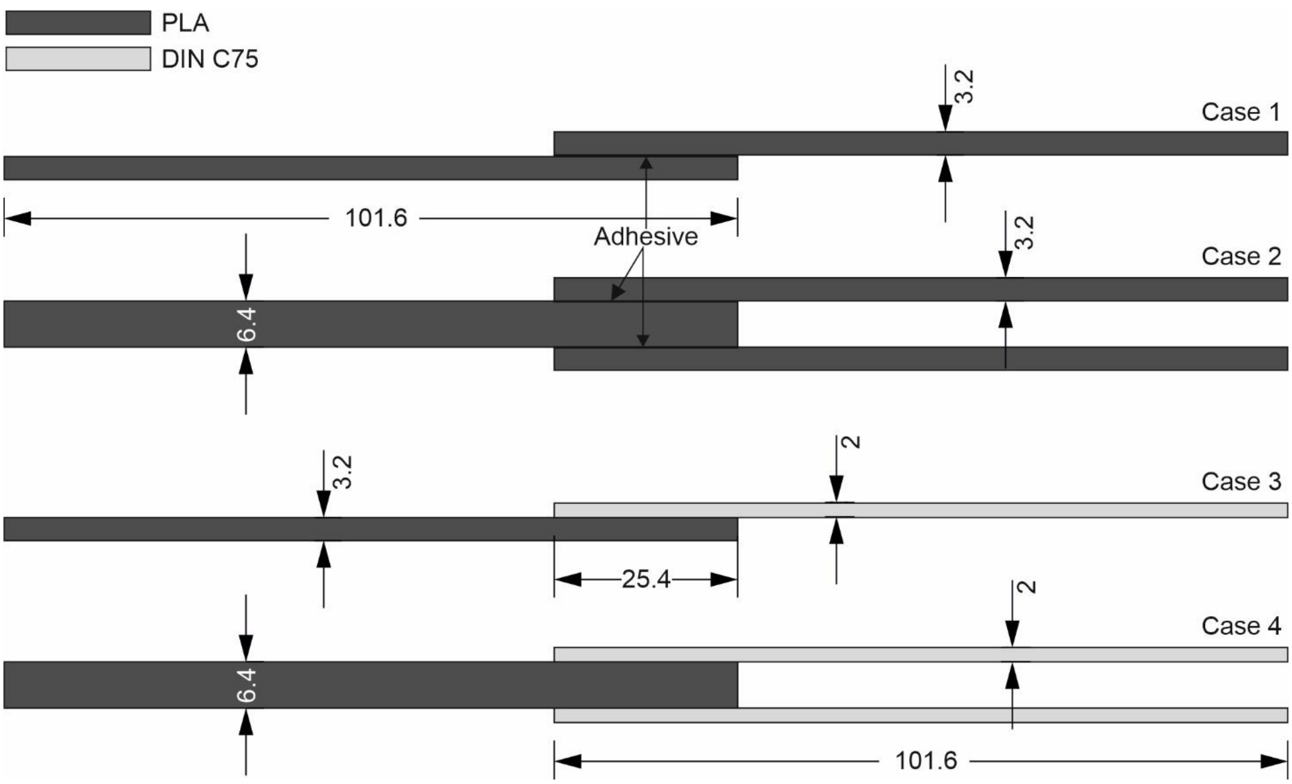

Figure 1. All joint configurations (dimensions in mm)

Table 1. Mechanical properties of substrates [25,26]

Properties	PLA	DIN C75
Young's modulus (MPa)	2850	198300
Tensile strength (MPa)	56	1413

Table 2. Properties of used adhesive

Chemical Type	Ethyl Cyanoacrylate
Components	One part -
Color	Slightly cloudy
Relative density (g/cm$^{3)}$	1.1
Specific Gravity @ 25ºC	1.05
Viscosity (cP) (at 1.5 rpm)	112000
Tensile Strength (MPa) [27]	20
Cure speed (at sec.)	5-120

The properties of the adhesive according to the technical data sheet obtained from the supplier are presented in Table 2.

2.2 Experimental Study

In this study, four joint configurations were investigated. These are the bonded SLJ and DLJ, induction welding SLJ and DLJ (Figure 1). SLJs and DLJs are fundamental types of adhesive joints that play crucial roles in various applications. SLJs are widely used and researched due to their simple geometry and structural efficiency [28]. They are preferred for their reliability and ease of implementation, making them a common choice in adhesive bonding [29]. On the other hand, DLJs offer specific advantages and are commonly used in thin structures under low running loads [30]. PLA+PLA in cases 1 and 2, PLA substrates in cases 3 and 4 were joined by induction welding to DINC75 substrate. SLJ and DLJ geometries are determined according to ASTM D3163-1 and ASTM D3528-96 respectively [31,32]. The overlap length and the thickness of the bond line were set similarly for all the prepared cases.

PLA+PLA joints (Case 1-2) were degreased by wiping with isopropyl alcohol along the tensile load direction prior to joining. Subsequently, adhesive was applied to the cleaned adhesion area, the other substrate was placed, and the joints were prepared with the use of metal clamps. The overlap length of the joints was measured with a digital caliper to check the dimensional accuracy. The technique used in cases 3 and 4, based on induction welding, is shown schematically in Figure 2.

The device represented in Figure 2 is a 30 KHz 50 kW induction machine manufactured by ONX (ONX, Turkey). The coil type with a diameter of 50 mm and a length of 65 mm was used as a bobbin on the device. The bobbin coil is a crucial component in induction welding systems, significantly impacting the efficiency and effectiveness of the heating process. The design and characteristics of the coil play a vital role in various aspects of the heating operation. For example, the use of a bobbin coil can result in improved temperature distribution, reduced process time, and enhanced heating efficiency in induction welding applications [33].

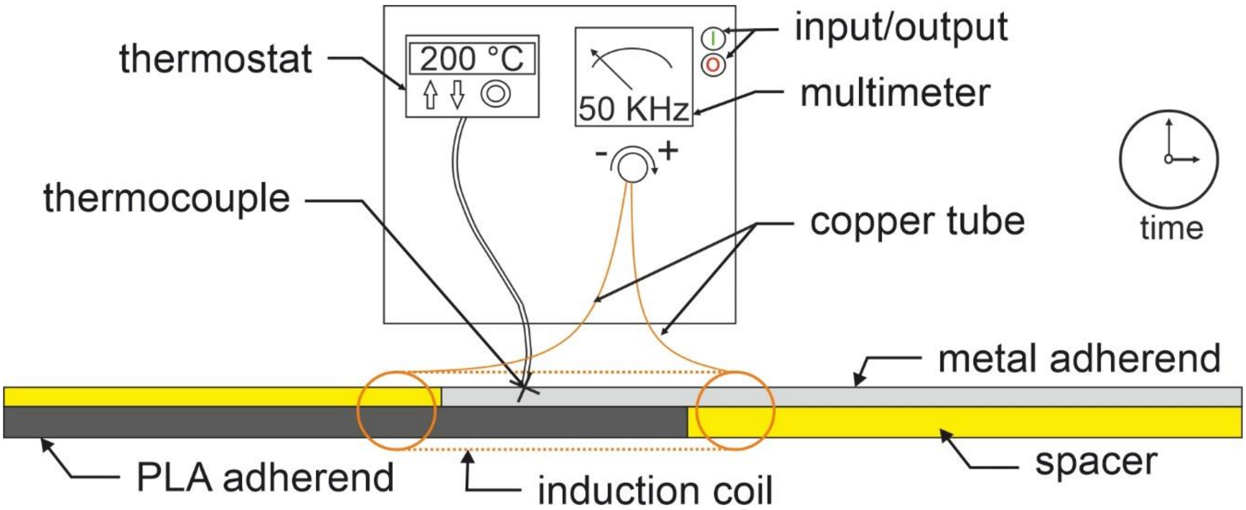

Figure 2. Schematic representation of induction welding technique

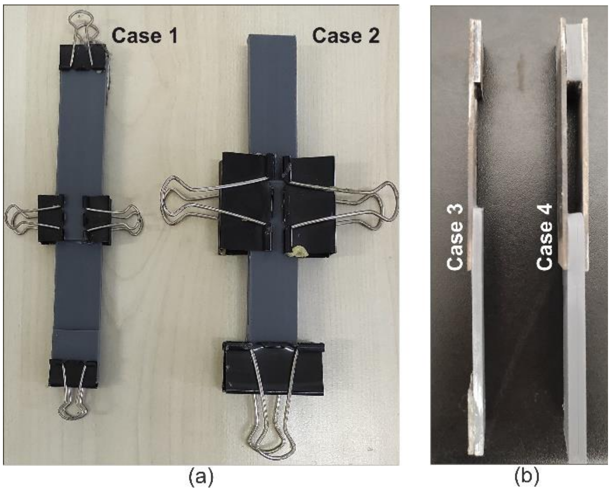

Figure 3. Produced specimens a) adhesive bonded and b) induction welded

Digital Thermostat (DT-48EM) thermostat was used to control the temperature on the substrate during the induction welding process. Prior to the bonding process, metal surfaces were prepared by sandblasting with silicon carbide and PLA surfaces were wiped with isopropyl alcohol. Induction welding was performed at 200 °C since the melting (Tm) and glass transition temperature (Tg) of PLA are 155-170 °C and 55-60 °C, respectively [34,35], and the decomposition temperature starts at 300 °C and ends at 375 °C [36]. Metal and polymer substrates were placed in the coil using a non-conductive mold. Subsequently, the joint was removed from the coil and the mold was applied pressure. The joints produced by adhesive bonding technology and induction welding are shown in Figure 3.

Mechanical characterization was performed under displacement control and at a test speed of 1 mm/min using a Shimadzu AG-50X (Kyoto, Japan) universal testing machine. Each characterization test was repeated at least three times, and load-displacement curves were acquired for each configuration.

3. Result and Discussion

3.1 Fracture Surface Analysis

The fracture surfaces of all joint cases are shown in Figure 4. When Figure 4 is considered, it is seen that cohesive damage is observed for the adhesive joints (Case 1 and 2). In the case of cohesive failure, it is understood that the adhesive has reached the maximum load it can carry [24]. When Case 3 and 4 are examined, it is clear that the damage is caused by the rupture of the thermoplastic material. In the case of adhesive joint and induction welding, the absence of adhesion failure showed that adequate surface preparation was carried out.

The cross-sections and top views of the damage areas in the induction welded cases were observed using an ISM-PM 200 SA digital microscope. Figure 5 shows the damage details of the joint in Case 3. When Figure 5 is examined, it is seen that the adhesion of the interface between DIN C75 and PLA is higher than the strength of PLA and therefore the damage is caused by PLA. In addition, when the interface was examined, it was observed that the bottom layer of PLA melted and bonded to the DINC75 surface. PLA has a brittle nature, which can lead to premature failure under stress. This brittleness is particularly evident in 3D printed samples where the layer-by-layer structure can form weak interlayer bonds. The mechanical performance of PLA parts is significantly affected by the fracture mode, which can be categorized as inter-layer and intra-layer fractures [37]. Inter-layer fractures occur due to poor bonding between layers, while intra-layer fractures are related to the intrinsic properties of the material [38]. As seen in Figure 5, intra-layer damage type was observed in PLA for Case 3.

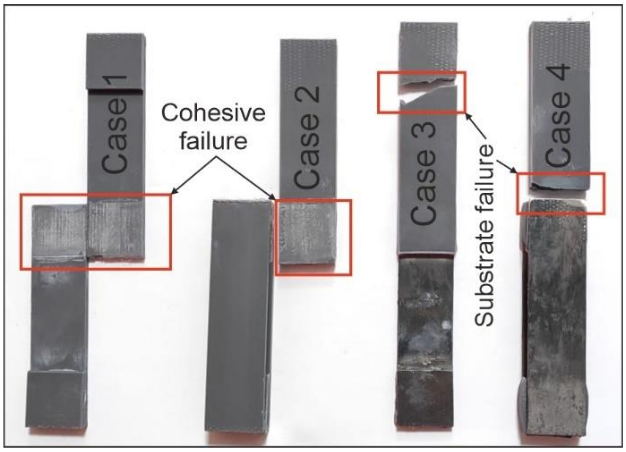

Figure 4. Fracture surface of all cases

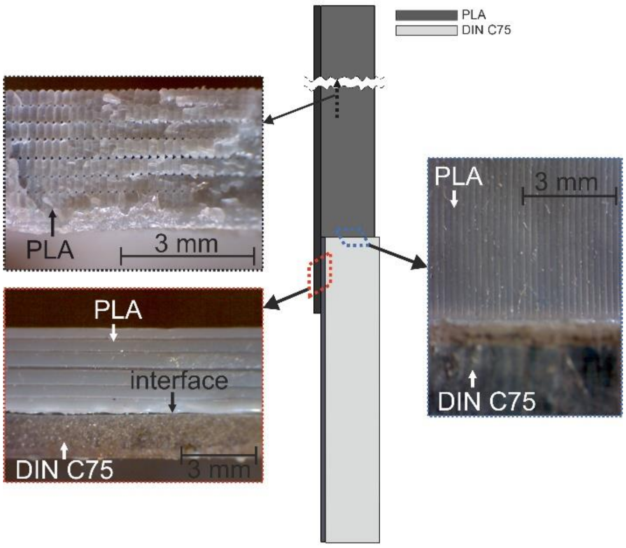

Figure 5. Fracture detail of Case 3

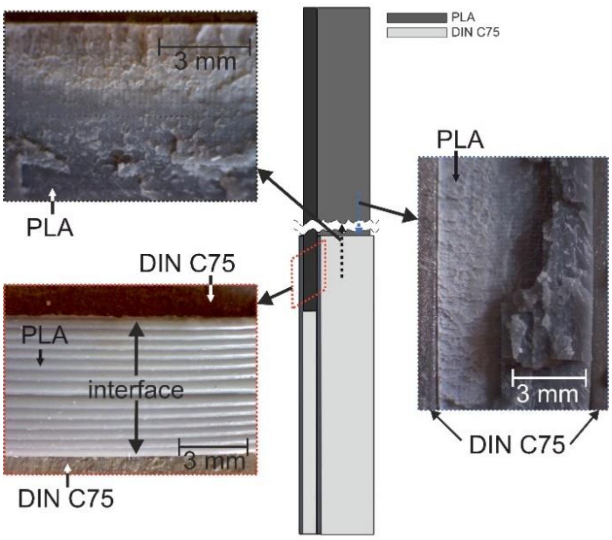

Figure 6. Fracture detail of Case 4

Figure 6 shows the damage states and detailed microscope images of the induction welded joint after the tensile test for Case 4. When using the SLJ geometry (Case 3), the induction coil only affects the single metal sheet. However, in DLJ geometry, in order to determine the effect of the induction process on the PLA sheet between two DIN C75 sheets, DLJ geometry was also preferred. As can be seen from Figure 6, the interface formed between PLA and two DIN C75 plates was formed by the melting of the top and bottom layers of PLA, and since the damage was caused by the PLA specimen, the strength of this interface was higher than the strength of PLA. Similarly, in Case 4, the damage of PLA was observed as intra-layer damage.

3.2. Tensile test results

Figure 7 shows the load-displacement curves of (Case 1 and 2) joined with adhesive. When these cases are compared, it is seen that Case 2 reaches the highest load-displacement value. Case 1 (i.e. the SLJ) rotates and suffers early damage due to significant joint rotations at the overlap edges [37,39]. This is due to the load asymmetry of Case 1 [40]. On the other hand, in Case 2 (i.e. DLJ), the rotation of the joint is eliminated as the load is symmetrically applied to the joint. Therefore, it has a higher load carrying capacity than Case 1 [41,42].

Figure 8 shows the load-displacement graphs of Case 3 and Case 4 prepared by induction welding method. Similar load-displacement behavior was obtained with the load-displacement behavior of adhesive joints. It was found that case 4 carried up to twice the load of case 3.

The failure load values of all prepared joints (adhesive and induction welded) are given in Figure 8. When Figure 9 is examined, it is seen that induction welding reaches the highest failure load in all joint types. Induction welded joints increased the failure load by 27.51% for SLJ and 65.49% for DLJ when compared to adhesively bonded joint. The reason that induction welding reaches a higher failure load than adhesive joints is due to the fact that, as previously outlined in Section 3.1, the maximum load that the adhesive can carry is reached in the case of an adhesive joint. Once the adhesive has exceeded the maximum load that it is capable of carrying, the damage is called cohesive damage. This damage means that the strength of the PLA is greater than the strength of the adhesive [39]. For this study, it can also be said that the interface formed between PLA and DIN C75 in the joints produced by induction welding (Case 3 and Case 4) is stronger than the adhesion strength and the PLA.

3. Conclusions

The effect of adhesive bonding and induction welding on the maximum load of joint of PLA+PLA and PLA+DINC75 substrates in SLJ and DLJ geometries was investigated. PLA substrates were produced using 3D printing technology. The impact of adhesive bonding and induction welding on the maximum load of joint was compared after uniaxial tensile testing of the joints. The main results obtained are listed below:

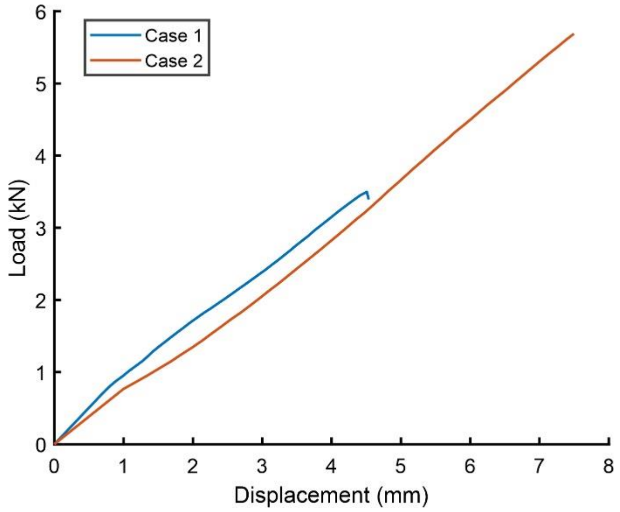

Figure 7. Load-displacement of adhesive bonded cases 1 and 2

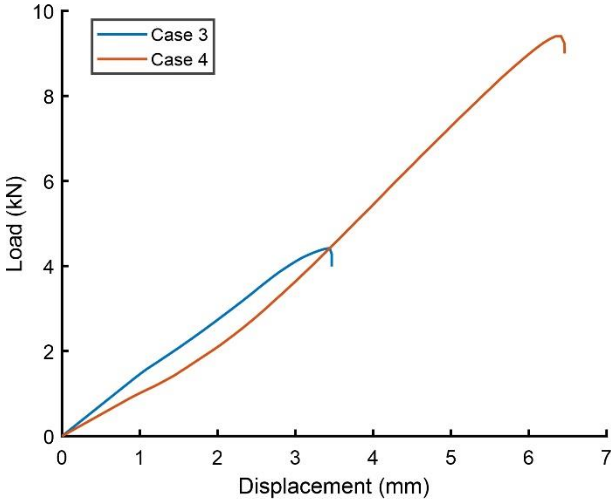

Figure 8. Load-displacement of adhesive bonded cases 3 and 4

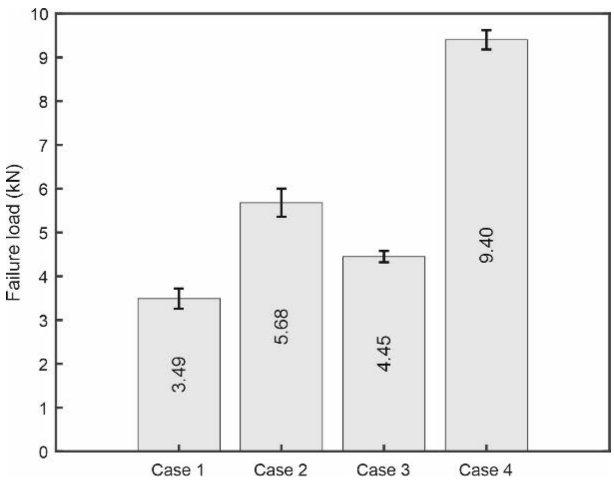

Figure 9. Comparison of failure load of all cases

- The maximum load of joint of adhesive bonding on PLA specimens was 3.49 kN and 5.68 kN for SLJ and DLJ geometries, respectively. Cohesive damage was observed in the adhesive joints (Case 1 and Case 2).
- The maximum load of joint of induction welding technology on PLA+DINC75 specimens was 4.45 kN for SLJ and 9.40 kN for DLJ. The induction welding method resulted in 27.51% and 65.49% increase in failure loads for SLJ and DLJ, respectively, compared to the adhesively joint. Induction welded joints (Case 3 and Case 4) showed substrate damage. In addition, the damage to the substrate was caused by the fact that the strength of the interface formed after the induction welding process between DIN C75 and PLA substrates was higher than the strength of PLA.
- No adhesive failure was observed in all joint configurations. This indicated that the two methods were used correctly and adequate surface preparation was performed.

These results suggest that induction welding is an important alternative to adhesively joining polymeric materials to steel.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

F.H. Öztürk developed the methodology, performed the experiments, analyzed the results and wrote the manuscript.

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