

# OVERVIEW OF JOINING DISSIMILAR MATERIALS: METALS AND POLYMERS

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**Abstract:** *This literature overview could serve to further understand the processes involved and how to optimize the techniques for obtaining enhanced metal to-polymer hybrid joints. There were analysed: mechanical fastening, adhesive bonding, surface functionalisation and different kinds of welding. Using the laser welding technology, different types of joints could be produced, that are difficult to be achieved by conventional joining methods, such as adhesive-bonding, mechanical fastening and thermal pressing. The best performances were observed for surface functionalisation of the metallic part combined with laser welding.*

**Key words:** *joining, dissimilar materials, polymers, metals, laser welding.*

## 1. Introduction

The need to combine the toughness of the metal with the chemical resistance and lightweight of the polymer requires the research of the dissimilar joining of metals with polymers. The main advantage of this kind of dissimilar joining is the enhancing of the design flexibility, using efficiently the main properties of each material [11]. These joining methods are: mechanical fastening, adhesive bonding and welding [6].

The aim of this paper is to analyse and summarize the results from the reference literature concerning different techniques for joining of dissimilar materials, with emphasis on polymers and metals. This paper could serve to better understanding of actual processes involved in dissimilar joining between materials like stainless steel, aluminium, magnesium and polymers.

## 2. Mechanical Fastening and Adhesive Bonding

In a complex study, Sadowski, T., et al. tested the aluminium-polyurethane bonding fastened with rivets [14]. The experimental results were compared with ABAQUS simulation. The number of rivets was varied between 1 and 9; the higher bearing capacity was found for 5 rivets. The best results were obtained for hybrid joints, their tensile strength being by 11% higher than analogous bonded joint and by 130% higher than mechanical fastening (Figure 1). The energy absorption during the failure process increased with 64% compared with the adhesive joint, due to addition of the rivets to the adhesive bonded joint.

Another mechanical joining method was tested by Paul, H., et al. [12], respectively joining of polyamide reinforced with 40% glass fibers (PA6.6 GF40) with HC420LA car

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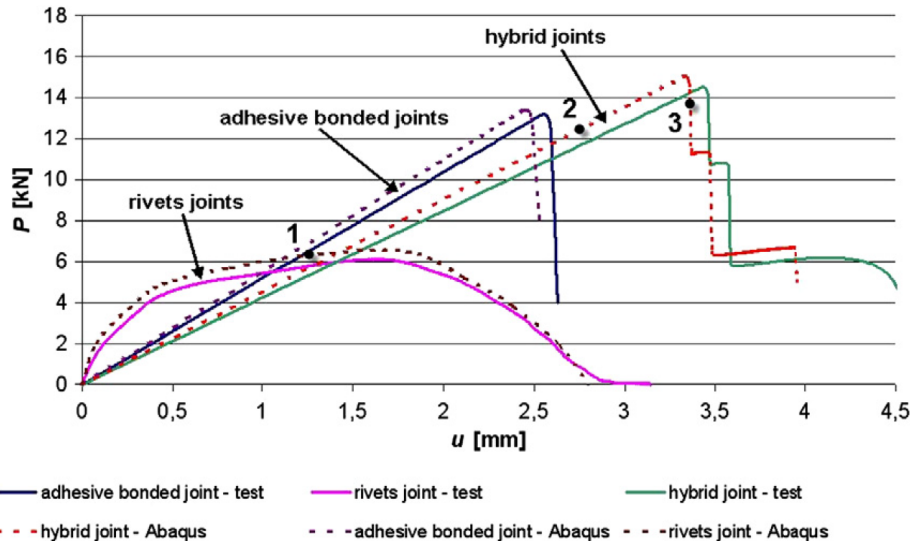


Fig. 1. Comparative tensile stress test results for different hybrid joining methods [14]

body steel. Three different joining mechanisms were observed during testing: force fit, direct adhesion and form fit. The results show that blasting with corundum of the metal surface and the form fit ( $\phi 6$  mm hole in the metal) increased the mechanical properties of the joining.

### 3. Surface Functionalisation

The surface treatment of metallic materials could improve adhesion and welding strength of metal-polymers dissimilar joints. Shimamoto, K., et al. [16] analysed the influence of surface preparation on the results of double cantilever beam test of dissimilar welding between glass fiber reinforced polypropylene and A6061 aluminium alloy. The samples surfaces were prepared by sandblasting (#120  $Al_2O_3$  grit) and chemical etching (AMALPHA treatment, proprietary technology of MEC Co. Ltd., Hyogo, Japan). After preparation, the welding process steps were as follows: compression with 0.1 MPa, heating from the aluminium side, cooling in the hot-press machine, removing of pression. The results show a critical energy release rate for the chemical etched specimens four times higher than those of specimens prepared by sandblasting. The results were not significant modified by increasing of the AMALPHA treatment depth from 2  $\mu m$  to 15  $\mu m$ .

Further improvement of the mechanical properties of metal-composite joints was investigated by Nguyen, A.T.T., et al. [10]. He made four types of hemi-spherical dimples and semi-cylindrical grooves on the metal surface (Figure 2) using Selective Laser Melting (SLM) method. Titanium was used as metallic material, co-cured to carbon fiber reinforced epoxy composite (T700 carbon/epoxy unidirectional prepreg plies). The investigation was based on mode I fracture toughness test. It was observed that interface strength of the hybrid structure is higher than interlaminar composite strength, the crack front being deflected from the metal-composite interface into the composite material. The best results were obtained for the outward groove feature, which increased the fracture

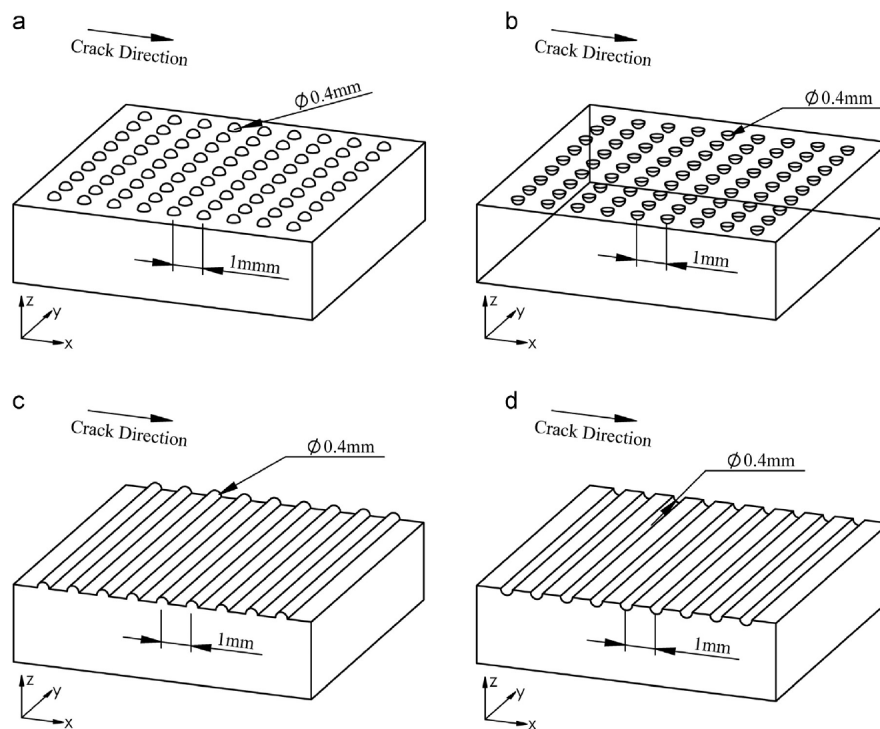


Fig. 2. Surface maximization using macro-features: a) outward dimple; b) inward dimple; c) outward groove; d) inward groove [10]

toughness of the joint by up to 50%, compared with composite material. This enhancing is due to increasing of the crack path length and shifting from pure mode I to mixed-mode crack.

With the same goal, Salstela, J. et al. [15] investigated the influence of the microscale structures silanization and oxygen plasma treatment on the aluminium/epoxy adhesion. The micro-mesh printing with a hydraulic press was used for microstructuring, creating on the aluminium surfaces mesh sizes of 100  $\mu\text{m}$ , 200  $\mu\text{m}$  and 400  $\mu\text{m}$ . Hierarchical microstructures were obtained onto aluminium using different combinations of micro-mesh printing and sandblasting. The micro-mesh structures improved the shear strength by 33% and the hierarchical micro-microstructures by 116%, compared to the untreated surface. The 20%  $\text{O}_2$  plasma improved the shear strength with 24%, compared to the untreated surface. The shear strength was not significant influenced by the oxygen contents of the plasma. Silanization with 3-glycidoxypropyltrimethoxysilane improves adhesion up to 68%, the low silane content giving the highest strength.

#### 4. Welding

Friction stir spot welding is a useful method for joining of dissimilar materials [9]. Goushegir, S.M., et al. [3] tested the influence of the friction spot welding parameters on metal/composite joining. The metal (AA2024-T3) samples were softly dry ground using P1200 SiC paper and sandblasted prior to welding. Both the metal and the composite samples were cleaned in pressurized air, washed in acetone ultrasonic bath and air dried.

The samples were welded using rotational speeds in the range of 1000-2900 rpm, plunge depth of 0.5-0.8 mm and joining force between 6.8-13.8 kN. The microscopic inspection reveals consolidated polymer in the aluminium surface pores and carbon fibers embedded in the deformed aluminium. Increasing of the rotational speed determines the enlargement of the joining area, which has as consequence the growth of the lap shear force and larger displacement. Increasing of the tool plunge depth improves the micro-mechanical interlocking of the dissimilar materials.

Liu, F.C., et al. investigated the influences of friction lap welding parameters on bubbles and shear strength [8]. The tested materials were AA6061 aluminium alloy and MC Nylon-6. Unlike friction stir welding, the friction lap welding does not have a stir pin and the main function of the rotation is to press and heat up the metal part, not to flow materials around the stir pin [8]. It was observed a linear relationship between the friction lap welding parameters (rotation rate)<sup>2</sup>/welding speed and the thickness of melted nylon. The increasing of the rotation rate bends the aluminium plate and increases the thermal input, resulting in decreasing of the bubbles volume and enhancement of the joint shear strength. The increasing of the welding speed reduces the thermal input and also the bubbles volume.

Katayama & Kawahito developed a rapid laser technique for dissimilar joining of metal-polymer without adhesives or glues [4]. The joints were realized between 2 mm thick PET sheet, overlapped with 30 mm on AISI 304 stainless steel plate, thickness 3 mm (Figure 3). Because of the 90% transparency of PET, the steel surface is heated by laser beam, that melts and partly decomposes the PET. As consequence of the occurrence of these pyrolysis gases, many submillimetre bubbles are formed inside the plastic near the joint. In TEM characterization of the samples revealed a tightly bonding at atomic, molecular and nanostructural level through the superficial Cr oxide film of the stainless steel. This method was named **L**aser **A**ssisted **M**etal and **P**lastic joining method (LAMP) [5].

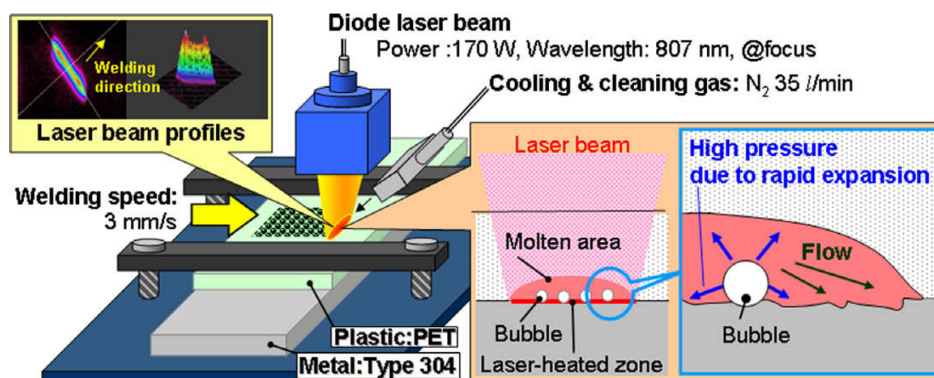


Fig. 3. Linear diode laser beam direct joining of metal and plastic and the formation of bubbles [4]

The LAMP method was also used by Lambiase & Genna to join 1 mm thick AISI 304 stainless steel with 2 mm thick polycarbonate using a 200 W diode laser [7]. The main joining defect, the tunnel defect (complete detachment of the materials), was obtained due to coalescence of bubbles caused by gas expansion at the PC-steel interface when linear energy was high. Increasing of the linear energy leads to increasing of the bonded area

and also growth of the bubbles dimension. Best joining shear strength (3.7 MPa) was obtained for linear energies between 36 and 40 J/mm, that created temperatures of 200-230 °C.

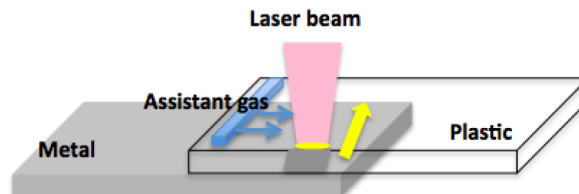


Fig. 4. *Direct laser joining setup used for AISI 204/PA66 welding [1]*

Another experimental study was performed by Fortunato, A., and team [1]. The chosen materials for joining were stainless steel AISI 304 sheet, 1 mm thickness, in overlap with 3 different polymers, PA66, PA66 with 35% glass fiber reinforced and PA66 with 40% carbon reinforced fiber, all the polymer thickness having 2 mm thickness. For testing was used a 100 W diode laser assisted by inert gas (Figure 4). The results of the tensile test show a good behaviour of the joining, the failure being in the heat affected zone. There were not recorded any significant variations of the tensile stress modifying the welding speed for non-reinforced opaque PA66. The tensile stress of the transparent PA66 is directly influenced by the welding speed.

Wahba, M., et al. used the LAMP technique to join AZ91D magnesium alloy with PET using 3 kW diode laser [18]. The irradiation was done from the metal or from the PET side, using different laser powers. In the last case, the authors also studied the influence on metal functionalizing, by melting the surface to create few pores near the surface and then ground to open the pores. The authors concluded that metal-side laser irradiation is better than plastic-side irradiation, in terms of joint strength, caused by different morphology: discrete bubbles in the first case vs. wormhole in the second one. This wormhole network was explained by the multiple reflection of the laser beam in the case of plastic-side irradiation (Figure 5). Surface functionalizing improves the join strength.

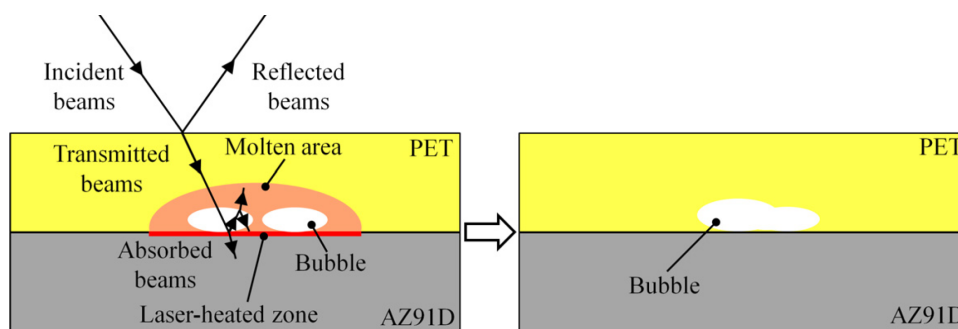


Fig. 5. *Mechanism of bubbles coalescence for the plastic-side irradiation [18]*

Roesner, A., et al. studied the effect of surface functionalisation on laser and induction welding of AISI 304 stainless steel with different type of polymers [13]. The microstructuring of the surface is the result of both sublimation and melting and the evaporation pressure generated by laser beam ejects the surrounding melt towards the specimen surface (Figure 6).

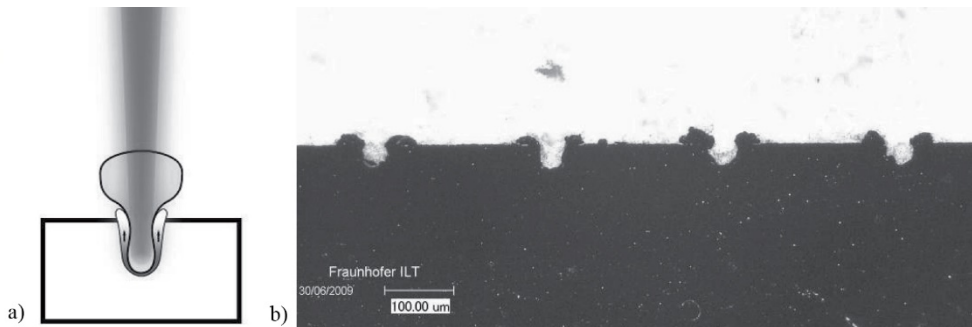


Fig. 6. a) Principle of the surface microstructuring; b) cross section of the joining [13]

A pulsed Nd:YAG disc laser was used for surface microstructuring ( $P = 40$  W,  $F = 22.5$  kHz,  $S = 450$  mm/s). The dimensions of the grows were approximately  $40\ \mu\text{m}$  width and  $50\ \mu\text{m}$  depth. The laser welding was done by metal-side irradiation, with a diode laser system at  $250$  W and  $800$  mm/s speed. Three types of plastics were used: polycarbonate, polyamide and glass fiber reinforced polyamide. The induction welding was performed with an induction coil on the metal part, for stainless steel with two types of plastics: polyamide and glass fiber reinforced polyamide. Using PA66, the best results in terms of shear stress were obtained for laser welding of the structures samples ( $16$ - $17$  MPa), followed by induction joining on the structured samples and induction joining of untreated samples. For PA66GF30, the best results were obtained by induction joining of the structures samples ( $20$ - $23$  MPa), followed by laser welding on the structured samples. The shear strength for the laser welding of the PC structured samples was  $14$  MPa. For the laser transmission joining, the shear strength is raised with the increasing of the structure density.

Fuchs, A.N., et al. applied both surface functionalisation and friction press joining for welding of 6082 aluminium alloy with glass fiber reinforced polyamide [2]. Friction press joining method is similar with the friction lap welding. Macroscopic surface functionalisation was done using the Surf-Sculpt method. The laser beam generates a melt pool at the surface. The pins are created based on the humping phenomenon, melt being accelerated in the opposite direction of the laser motion (Figure 7).

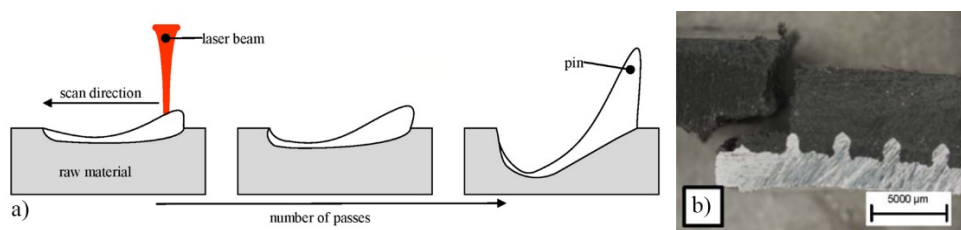


Fig. 7. a) Principle of the Surf-Sculpt method; b) microscopy of the tapered pins [2]

Microscopic surface functionalisation was done using the **Remote Ablation Cutting (RAC)** method. The laser beam attacks with high velocity the surface, partially evaporating the material. Because the vapor pressure ejects the surrounding melt, there are generated superficial kerfs. For welding was used a  $\phi 15$  mm tool moved with  $800$  rpm at  $240$  mm/min feed rate. The axial force was between  $1.5$  kN and  $2.0$  kN. The test results show the decreasing of the shear strength with increasing of the macroscopic pin height,

that weakened the joint by the larger notch effect. Tapering of the pins increases the shear strength. By increasing the laser power for RAC were generated deeper kerfs and larger undercuts, resulting in higher shear strengths. The best results were obtained for 900 W.

Van der Straeten, K., et al. studied both surface functionalisation (con-like protrusion, Figure 8) and laser joining of AISI 304 austenitic stainless steel with PA6 having 47% vol. glass fiber reinforcement. For surface functionalisation through ablation was used an ultrashort pulsed laser ( $P = 50$  W,  $F = 800$  kHz) and the welding process was carried out using a continuous laser ( $P = 300$  W).

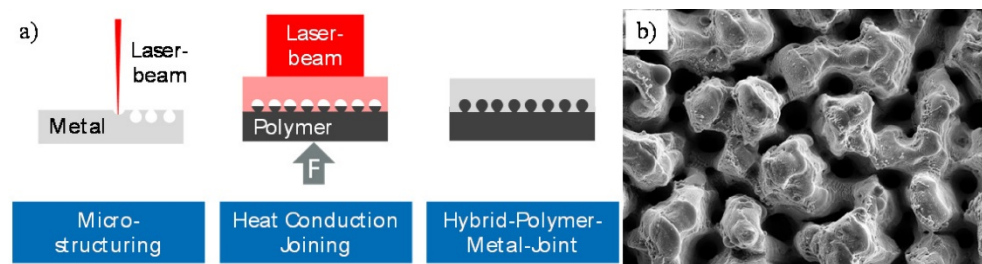


Fig. 8. a) *Steps of the laser based metal-polymer connection using surface microstructuring with con-like protrusions; b) SEM of the metal surface* [17]

After melting, the polymer was pressed (4 bars) against the functionalised surface using a pneumatic clamping device. The bonding strength was greater than 25 MPa, higher than adhesive bonding and other laser welding methods.

## 5. Conclusions

Nowadays, different methods are available for joining of dissimilar materials. While mechanical fastening increases the number of parts and operations, adhesive bonding is a good choice, but requires the previous surface treatment and the operating temperature is limited. Surface functionalization followed by laser processing can produce high quality dissimilar joints between metals and polymers strong bonded at the molecular level.

There were presented different solutions for surface functionalisation combined with laser welding able to ensure good mechanical properties, higher than adhesive bonding and friction stir welding.

Using a laser welding system with different parameters provides the possibility to improve the adhesion and joint strength of hybrid materials. Formations of bubbles or other micro structuring on the metal part are powerful properties to performance a strong bond between polymers and metals.

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