Rev. Adv. Mater. Sci. 36 (2014) 152-164

TECHNIQUES FOR JOINING DISSIMILAR MATERIALS: METALS AND POLYMERS

Paul Kah, Raimo Suoranta, Jukka Martikainen, Carl Magnus

Lappeenranta University of Technology, PO Box 20, 53851 Lappeenranta, Finland

Received: August 12, 2013

Abstract. Techniques for joining lightweight dissimilar materials, particularly metals and polymers, are becoming increasingly important in the manufacturing of hybrid structures and components for engineering applications. The recent drive towards lightweight construction in the aerospace and automotive industries has led to increased exploitation of lightweight metallic and non-metallic materials with the aim of achieving specifically optimized versatility. Hence, suitable joining methods are necessary in order to reliably join these dissimilar materials and to integrate them in engineering structures. Understanding of the various joining technologies that exist for multi-material metal-to-metal, polymer-to-polymer, and metal-to-polymer hybrid structures is consequently important. The objective of this current study is to examine and summarize information and results from previous research and investigations on techniques for joining dissimilar materials. The findings presented serve to further understanding of the various joining techniques available and optimization of processes for metal-to-metal, polymer-to-polymer and metal-to-polymer hybrid joints.

1. INTRODUCTION

Utilization of plastic materials in engineering structures has increased because of benefits accruing from their low weight, high specific strength and elastic modulus, design flexibility, and reduced manufacturing costs [1,2]. The growing prevalence of polymer materials in structural applications has spurred research into the combination of dissimilar materials and joining methods – a critical factor in the manufacturing of components involving polymers and metallic materials [1]. Parts made by combining dissimilar materials such as metal-to-metal, polymer-to-polymer, and metal-to-polymer are nowadays in high demand. For example, such parts are used in the automobile and aerospace industry, where they are made of hybrid components from lightweight dissimilar materials such as aluminum or magnesium alloys and fiber-reinforced polymers [3-5].

One of the aims for the use of dissimilar joints is to enhance product design flexibility, allowing the differing materials to be utilized in an efficient and functional manner based on the specific properties of each material. Examples of metal-to-metal combinations can be seen in applications such as steam turbine diaphragms (2 1/4Cr-1Mo/C-Mn steel), power generation systems (2 1/4Cr-1 Mo/AISI 316), electromagnetic devices (Cr-Ni alloy/Ep517), and heavy equipment (SAE1136/1010 steel) [6]. Similarly, polymer-to-polymer joints facilitate design flexibility by exploiting strength properties close to the parent material. A typical example can be seen in the joining of thermoplastic matrix composites and thermosetting-based composites [7]. Metal-to-polymer joints, on the other hand, combine the strength and ductility of the metal with the physico-chemical resistance and light weight of the polymer [5]. The metal component is utilized in sections where high stiffness and strength can be exploited, whereas the plastic material provides unique chemical properties, and enables further functional integration via

Corresponding author: Paul Kah, e-mail: paul.kah@lut.fi

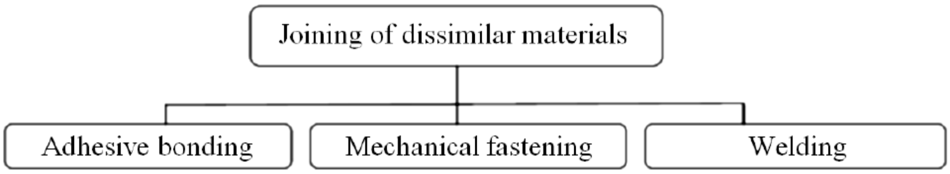


Fig. 1. Joining methods for dissimilar materials, adapted from [10].

the formation of complex shapes in the molding process [8].

In structural applications, it is therefore important to maximize effectively the joint contribution of each material in order to ensure optimal mechanical performance while still maintaining a weight- and a cost-effective solution [8]. However, joining of dissimilar materials is often difficult to achieve and the behavior of such joints is rarely fully understood, particularly when using bonding and heating techniques. The most frequently used joining methods for dissimilar materials are mechanical fastening and adhesive bonding [9]. However, these joining processes present several limitations, such as stress concentration, the demand for extensive surface preparation, extra weight, material metallurgical differences and harmful environmental emissions.

Promising welding techniques and approaches for joining dissimilar materials have been developed as a way to address problems related to traditional joining techniques. Examples of such new emerging techniques are laser welding, ultrasonic welding, friction spot welding, and friction stir welding. The effective application of these processes necessitates an understanding of the processes and the behavior of metals and polymers in the processes, as well as knowledge of the capability and limitations of the joining processes when joining dissimilar materials.

This paper presents a comprehensive overview of joining techniques for dissimilar materials found in metal-to-metal, polymer-to-polymer and metal-to-polymer joints. The paper comprises four sections. First, general concepts and the need to join dissimilar materials are explained. Second, the various methods of joining dissimilar materials are presented. The third part of the paper focuses on welding of dissimilar materials. Welding receives particular attention since it is an emerging technology with promising future prospects in the joining of dissimilar materials. The welding of metal-to-polymer is given greater emphasis in this section than metal-to-metal and polymer-to-polymer welding, since metal-to-polymer is a novel technique and there are fewer publications in this area. The final section of the paper presents concluding remarks about the topic, summarizing the advantages and disadvantages of the approaches and techniques discussed.

2. JOINING METHODS FOR DISSIMILAR MATERIALS

Several joining techniques exist for hybrid joints between metal and polymer workpieces. These methods are divided into groups as shown in Fig. 1; adhesive bonding, mechanical fastening, and welding [10]. The processes can be utilized individually or combined in a single technique to ensure a successful and durable joint between the metal and polymer in the hybrid structure. It should, however, be noted that these joining techniques have their advantages and disadvantages and the most appropriate method will depend on application and service requirements.

2.1. Adhesive bonding

Adhesive bonding is a solid state joining technique that relies on the formation of intermolecular forces between the workpieces and the polymeric adhesive itself for joint formation [11]. Adhesive bonding involves the use of a polymeric adhesive, which undergoes a chemical or physical reaction, for eventual joint formation.

In recent years, the use of adhesive metal joining has grown substantially due to the development of high-strength and tough adhesives that can withstand both static and alternating loads [12]. The drive towards considerable weight reduction in aeronautics, aerospace, and automotive applications has contributed to the rapid development of this joining method, which offers unique weight reduction along with homogeneous stress distribution during loading [12]. However, adhesive bond joints can prove to be problematic, as the bonded joints cannot be disassembled without damage. Moreover, the joints are prone to environmental degradation from factors such as moisture, humidity, and temperature [13]. The most important factor limiting the use of adhesive bonding is, however, uncertainty in forecasting the long-term durability of this kind of joint and difficulties in carrying out reliable non-destructive test-

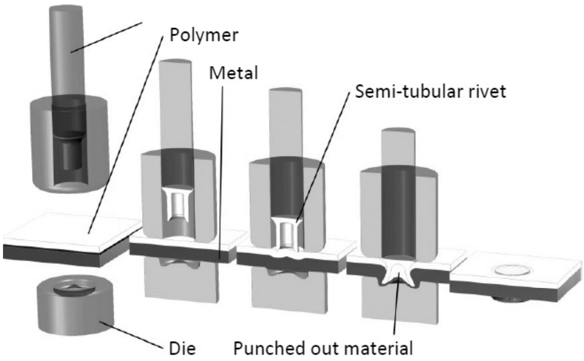


Fig. 2. Schematic presentation of metal-to-polymer riveted joint, adapted from [22].

ing. A further limitation is the fact that bonded joints often fail instantaneously instead of progressively when applied in engineering structures [12].

The workpiece surface properties in an adhesive bond play a vital role in the bonding process, and bond strength and joint durability can be significantly improved by surface treating the workpieces prior to the bonding. During surface pretreatment, the surface energy of the workpieces increases, but the contact angle of water decreases and the surface tension increases. Typical surface pretreatment techniques include solvent cleaning, alteration of surface chemistry, and abrasion and other topographical changes. Environmental factors have a strong influence on the durability and ultimate mechanical performance of an adhesive bond joint. The most important environmental factors are climatic factors, such as temperature and humidity.

2.2. Mechanical fastening

Mechanical fastening incorporates the use of additional clamping components without fusing the joint surfaces. It relies on the use of clamping or members such as screws and rivets for eventual joint formation. Features of mechanical fastening include [14]:

- a heating cycle during which the rivets utilized for clamping are heated prior to the fastening so that upon cooling, the rivets shrink enabling the component to be clamped tightly [15] However the heating is used only for some type of riveting;
- special mechanical operations required by the method, such as drilling of holes, making screw threads etc., prior to the joining process [16,17];

Different kinds of mechanical fastening still remain the most used method in joining components due to the simplicity of the process [18]. Originally, mechanical fastening was used to join metallic materials (metal-to-metal) but it can now be employed in the joining of plastics (polymer-to-polymer) and also metal-to-plastic [18]. However, it comes with limitations, such as increased component weight and evolution of stresses around fastener holes, which induce strength degradation and eventually create corrosion related problems [19]. Different types of mechanical joining techniques exist for metal-to-plastic joints but the emphasis is currently on riveting, as it establishes a reliable joint [20].

Joint configuration often depends solely on service conditions; an example is whether leak tightness is required. In some cases, the joint may be designed to tolerate mismatch in the coefficient of thermal expansion during assembly. Joints can also be made to allow complete freedom of movement in the plane perpendicular to the clamping member. Settineri et al. [21] investigated self-piercing riveting for metal-to-polymer joints. Fig. 2 shows a typical self-piercing riveting procedure. Experimental results showed that in rivet joining between a metallic and polymeric material, the process depends on the geometric parameters of the rivet, such as sheet thickness and tool design, and the riveting force.

Due to the fact that the bottom material sheet undergoes the highest deformation, it is important to place the metallic sheet as the bottom sheet and the polymeric material as the upper sheet [23]. Metal-to-polymer hybrid joints present unique properties and efficiency in terms of design and manufacturing flexibilities, along with overall weight reduction.

However, both mechanical fastening and adhesive bonding necessitate an overlapping joint configuration to achieve the required joint strength, which however increases the weight, thickness, and stress concentration of the structure [24,25]. This limitation in joint design restricts the use of these joining techniques. It is therefore important to develop a joining technique for dissimilar materials that has greater design flexibility and fabrication rates than adhesive joining and mechanical fastening [26].

2.3. Welding

Conventional welding processes such as shielded metal arc welding, gas tungsten arc welding, gas metal arc welding, and submerged arc welding have been used to weld dissimilar materials in metal-to-metal joints. Nevertheless, the high energy inputs of these fusion welding processes result in material metallurgical mismatch [6], thus hinder their use in dissimilar metal-to-metal joints as well as polymer-to-polymer and metal-to-polymer joints.

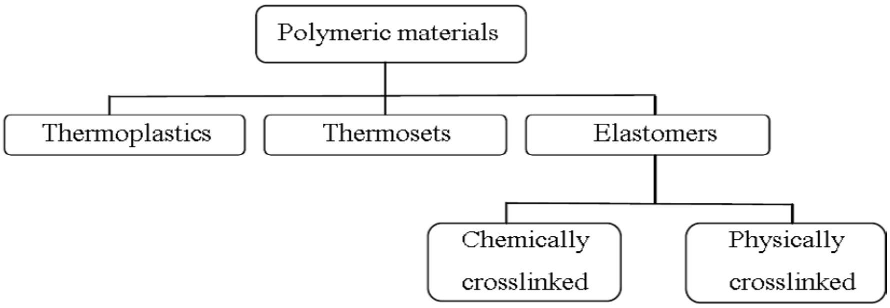


Fig. 3. Classification of polymeric materials, adapted from [10].

Welding of dissimilar materials with new emerging techniques such as laser welding, ultrasonic welding, friction spot welding, and friction stir welding is somewhat more feasible, because polymeric materials such as elastomers, thermoplastics, and thermosets, [9,11] as shown in Fig. 3, comprise structural macromolecules that are held together by the Van der Waals force, whereas metals consist of densely packed crystal structures with high cohesive energy [10,27,28]. The melting temperature of metallic materials is extremely high compared to the polymer melting temperature. Hence, polymers tend to degrade before metals melt [9].

However, although thermoset and thermoplastic polymeric materials can be both adhesively bonded and mechanically fastened, welding can only be employed on thermoplastics [9,10]. This limitation exists because the processing of thermosets and chemically cross-linked elastomers is characterized by an irreversible crosslinking reaction which results in degradation; hence, they cannot be reshaped by means of heating [9-11]. On the other hand, thermoplastics and thermoplastic elastomers can be melted and softened by heat due to the weakening of the secondary Van der Waals and hydrogen bonding forces among interlocking polymer chains [9]. This makes it possible for thermoplastics and thermoplastic elastomers to be remolded upon application of heat, and they can, consequently, be fusion welded [9].

3. EMERGING TECHNIQUES FOR JOINING DISSIMILAR MATERIALS

Efficient and effective ways of joining dissimilar materials by welding techniques such as ultrasonic welding, laser welding, and friction spot welding have increased productivity in industries such as the automobile industry and have also helped to solve problems related to traditional joining techniques. This section elaborates on the principles and prospects of such emergent techniques in welding of dissimilar materials such as metal-to-metal, polymer-to-polymer and metal-to-polymer.

3.1. Ultrasonic welding

Ultrasonic welding is a solid state joining technique that initiates coalescence via the simultaneous application of localized high-frequency vibration energy with a moderate clamping force [29]. This welding technique is characterized by low energy input and requires the clamping and positioning of the workpieces between the welding tool (sonotrode) and an anvil by static force. The workpieces in ultrasonic spot joining can be two thin sheets and thick-thin sheets combinations in a simple lap joint [30] or a butt joint depending on the direction of supply of the energy of elastic oscillations to the welding zone [31]. Ultrasonic vibration can be applied to welding both metals and plastics, but the welding process differs, and the actual weld achieved depends on how the ultrasonic energy (vibration) is delivered to the weld [30].

In ultrasonic metal welding, the direction of ultrasonic oscillation is parallel to the weld area. When ultrasonic metal welding is realized, the frictional action of the workpiece surfaces initiates a solid

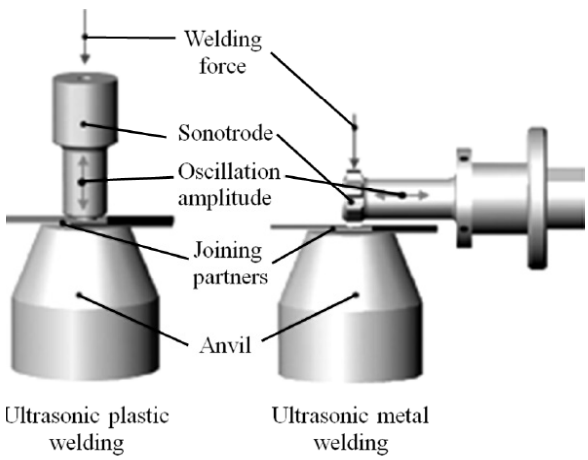


Fig. 4. Schematic comparison between ultrasonic plastic and metal welding, adapted from [30].

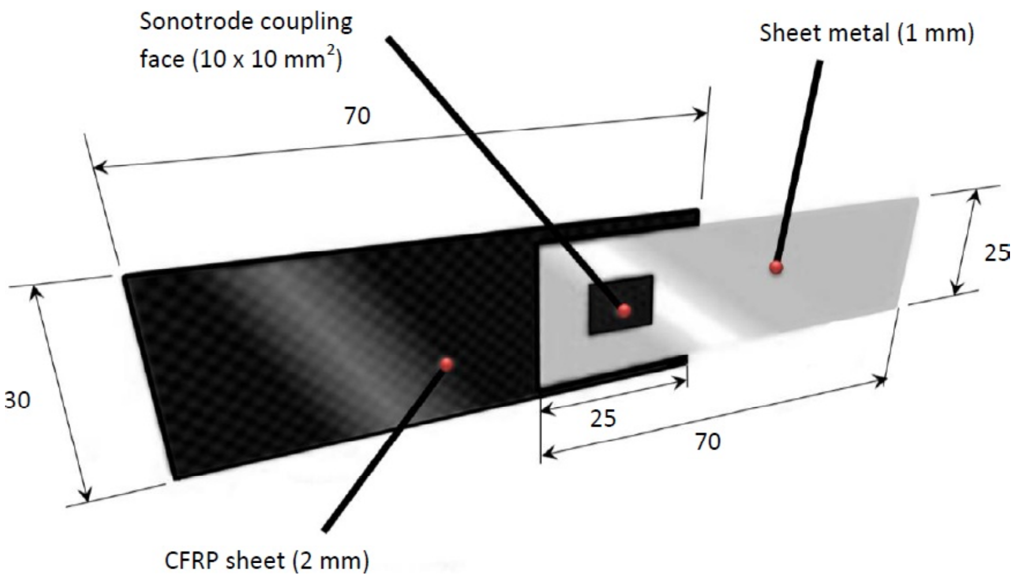


Fig. 5. Typical specimen geometry for CFRP/ Al joint, adapted from [30].

state bond without any melting action of the workpieces; the reverse is the case in plastic welding. For ultrasonic plastic welding, the direction of ultrasonic oscillation is perpendicular to the weld area, as shown in Fig. 4 [30].Ultrasonic plastic welding brings about melting and fusion of the workpiece material at much lower temperatures than arc or laser welding processes.

Balle et al. [30] investigated the ultrasonic metal welding of aluminum sheets to carbon fiber-reinforced thermoplastic composites. Their experiment studied the weldability of aluminum alloy 5754 and carbon fiber-reinforced polymer (CFRP) with thicknesses of 1 mm and 2 mm respectively as shown in Fig. 5.

It was observed that a safe and sound weld occurred at amplitudes around 40 μm due to displacement of the CFRP matrix, thus leading to a better contact between the metal sheet and the fiber. It was also observed that intermolecular reactions in the weld zone formed when oxide layers on the metal sheet peeled off during the welding process, whereas the polymer matrix displaced out of the welding zone in order to allow the ductile aluminum to adapt the carbon fibers. This however enabled mechanical interlocking between the joining partners and consequently increased the joint strength. It was finally observed that the carbon-fibers surrounded the aluminum alloy as a result of the plastic deformation of the aluminum sheet, thus creating a successful weld between the metal and the polymer [30].

3.2. Laser welding

Laser welding is a welding technique which offers unique manufacturing opportunities. It complements the fabrication and processing of joints which previously had been difficult or impossible to achieve by other welding methods [32]. Recent investigations in laser welding of dissimilar metals include laser welding of Ti6Al4V and lead metal; and laser welding of TiNi shape memory alloy and stainless steel using cobalt (Co) filler metal. In the laser welding of Ti6Al4V and lead metal, it was observed that the strength of the joint obtained between the two dissimilar metals was at least equal to or higher than the strength of the lead base metal [33]. In laser welding of TiNi shape memory alloy and stainless steel using Co filler metal, it was noticed that the performance of the weld joint strength between the two dissimilar metals would be excellent if a suitable thickness of Co filler metal was chosen [34]. Thus, laser welding of dissimilar metals can sometimes guarantee higher joint strength than even the strength of one parent metal.

Polymeric materials can be welded with different types of laser sources but the welding process depends on the laser wavelength. The introduction of the high-power fiber laser, which has a wavelength around 2 μm, facilitates the welding of polymers even though the absorption rates of the polymers may be different. However, welding polymeric materials with laser sources that have visible and near-infrared wavelength around 1 μm requires the use of an additive to increase the absorption of the laser radiation [35]. If not laser-sensitized, the laser beam incident on the polymer surface will be mostly transmitted and the heat required for fusion cannot be achieved due to an absence of absorption. Furthermore, without the use of additives, polymeric materials can only be processed in far-ultraviolet light

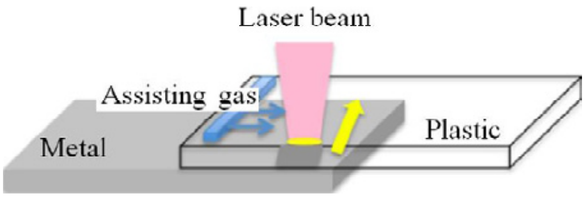


Fig. 6. Schematic presentation of a laser-assisted metal-to-plastic joining process, adapted from [38].

with excimer lasers and in far-infrared light with CO_2 lasers. As mentioned earlier, their chemical structure means that only thermoplastics and thermoplastic elastomers, either amorphous or semi-crystalline, can be fusion welded [36]. Thermosets are not laser weldable due to crosslinking, which hinders melting and remolding. The laser welding of polymers can be divided into two different processes, namely, butt welding and laser transmission welding [37].

In butt welding of two polymers, the connected surfaces are heated up close to melting with the laser beam, and the parts are then pressed together for eventual joint formation. It should be noted that for butt welding to be achieved, both plastic materials must be able to absorb the laser beam [37].
In laser transmission welding of polymers, one of the polymers, typically the top polymer, needs to be transparent to the laser beam while the other polymer absorbs the laser beam. The bottom, laser-absorbent polymer heats up and consequently melts. The heat transfers by conduction from the bottom polymer to the top transparent polymer, which melts, and the two parts are subsequently pressed together for eventual joint formation [37].

Laser direct joining methods between metals and polymers, typically known as the Laser-Assisted Metal and Plastic joining method, have been proposed as shown in Fig. 6 [38].

The physical phenomena occurring in the welding process are summarized as [41]:

- The metal-to-polymer joint interface is heated up by the incident laser beam, and melting temperature is attained in the plastic material in a narrow region adjacent to the interface;
- The resulting high temperature initiates the formation of bubbles in the melted plastic close to the interface;
- Bubbles spread and diffuse into the molten phase and consequently increase seam dimension;
- bonding results in the molten–solid interface between the plastic and the metal.

The bonding mechanism is due to the combined influences of chemical bonding between the metal oxide film and the carbon atoms of polymers, and the physical bonding phenomenon resulting from the Van der Waals force and mechanical bonding [41].

The physical phenomenon occurring during the welding process necessitates the need for overlapping joint configuration in this joining technique, as described above [40]. Due to the low thermal conductivity of plastics, this means that heat remains concentrated in the material interaction zone. Furthermore, the behavior of the heat will depend on the optical properties of the plastics, which are a function of its molecular composition, such as the colour of the plastic and the wavelength of the incident beam. In the case of optically transparent plastics, laser metal–plastic joining occurs only if the laser beam absorption is localized at the interface [40]. On the other hand, for optically opaque plastics, the laser beam must be focused on the external surface of the steel component. Heat is transferred via conduction from the heated steel component to the plastic component, which heats up and consequently melts.

Katayama et al. [39] investigated the laser direct joining of metal and plastic. In their research, a 807 nm wavelength laser beam from a diode laser was incident onto a 2 mm thick polyethylene terephthalate (PET) plastic sheet of 30 mm width overlapped on a 3 mm thick stainless steel plate Type 304. A shielding assisted gas, typically nitrogen, was employed with flow speed 35.1 L/min for cooling and to clean the plastic surface, as shown in Fig. 6. The diode laser beam was adjusted to obtain a line beam of length 1.2 mm and width 9.4 mm, generating a power density of 30 W/mm^2 with a laser power of 170 W. The laser beam traveling speed was maintained at 3 mm/s and the shielding gas nozzle was 0.5 mm long and 19 mm wide. The transparency of the plastic (PET) to the diode laser beam was about 90%. As the laser beam transmits through the transparent PET to the steel surface, the steel surface is heated up by the laser energy, which brings about melting and consequently decomposes the PET. As a result of the initiated high-temperature plastic melt, contact between the metal and plastic is established due to the generation of high pressure resulting from rapid bubble expansion.

Scanning electron and transmission electron (SEM/TEM) microanalysis were carried out on the joint interfaces, as shown in Fig. 7. The SEM images revealed the presence of bubbles close to the joint between Type 304 and the PET. The TEM images showed that the metal and plastic were bonded together on the atomic and molecular levels, as shown in Fig. 7B.

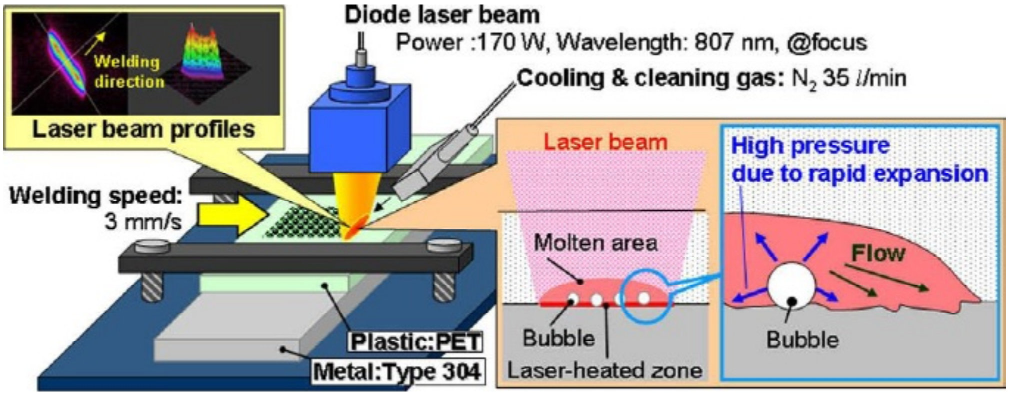


Fig. 7. Schematic presentation of direct metal-to-plastic joining with diode laser showing the process and bonding mechanisms, adapted from [39].

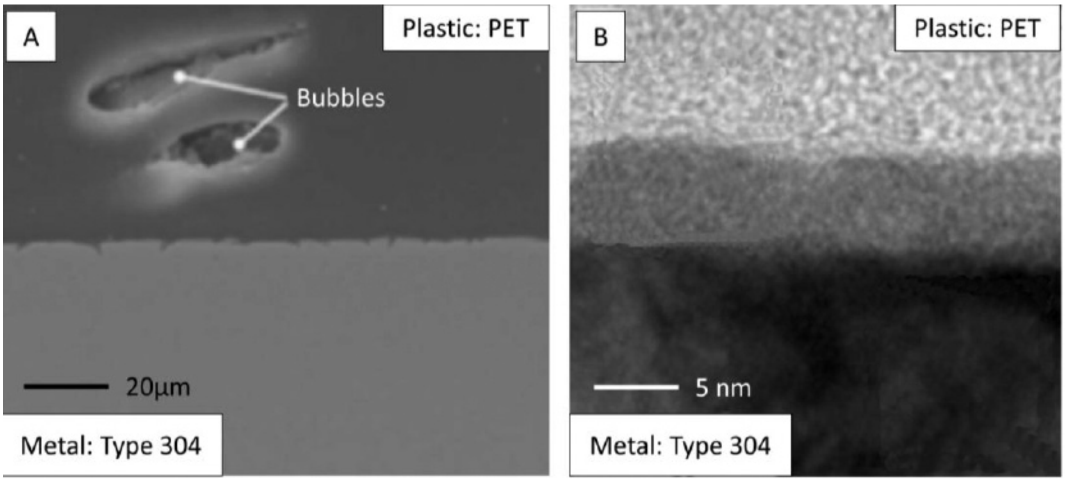
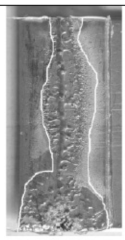
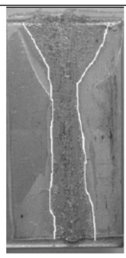
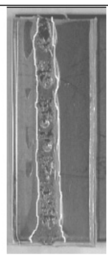
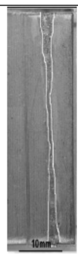


Fig. 8. SEM image (A) and TEM image (B) showing intimate contact of the PET plastic and steel 304, adapted from [39].

In another study, Tillmann et al. [42] investigated process optimization in the laser welding of metal to polymer. The investigation showed that when the laser power was varied between 40 W and 80 W, with other welding parameters kept constant, there was a corresponding increase in the fracture loads of the joints up to a specific level, which was followed by a decrease beyond this point, shown in Fig. 8.

It was observed that an increase in laser power brings about a corresponding increase in bond width, which influences positively on the fracture load, illustrated in Table 1.

Table 1. Influence of laser power on joint appearance, porosity formation, and bond width at fixed travel speed 32 mm/min, adapted from [42].

Laser power	80 W	70 W	60 W	50 W	40 W
Joint appearance					
% Porosity	62	25	27	38	33
Bond width	5.5 mm	4.4 mm	4.2 mm	2.7 mm	1.3 mm

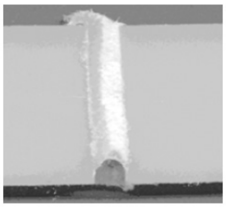
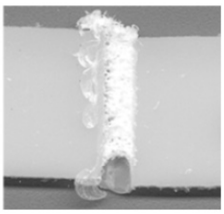
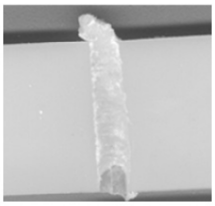
The measured average porosities were at maximum value when laser power was at its highest, 80 W. On the other hand, as the laser power decreased slightly, typically to 70 W and 60 W, there was a corresponding decrease in porosity and joints reached the highest fracture load. At still lower laser powers, 50 W and 40 W, it was obvious that the laser power was not great enough to completely melt the polymer part and partial wetting of the steel part was observed.

Based on observation of the joining process, it seems that the number and sizes of the pores play a vital role in the joining process. When the number/size of pores increases, a negative effect is dominant and the strength of the joint decreases. On the other hand, as the number and size of pores decreases, the positive effect is dominant and the joint strength increases, especially at laser power 70 W and 60 W. In addition to the influence of laser power on the joint strength, another important factor was observed to be the travel speed during the welding. It was noted that at the beginning of the joining process, the increase in laser travel speed lead to an increase in the fracture load that then decreased gradually, as shown in Fig. 9. 60 W and 70 W laser power broadly follow the same curve but 75 W and 80 W are very different. Measurements for 75 W and 80 W only start at around 38 mm/min whereas those for lower W values start around 12 mm/min. The lower W values might show the effect of heat input, which has a very narrow window before which the welding does not occur and after which chemical changes weaken either the welding bonds or the polymer. The higher W values might describe a combination of welding from heat input plus some other chemical change.

3.3. Friction spot joining

Friction stir spot joining is a variant of linear friction stir welding (FSW) developed by a Japanese corporation [43] to replace resistance spot welding of aluminum sheets [44-46]. This welding technique is similar to FSW except that there is no linear movement of the tool during friction spot joining (FSJ) [48]. During FSJ, the friction between the pin and the workpiece generates most of the heat energy for joining. This welding process incorporates three distinct phases: plunging, stirring, and retracting [47]. During the welding, a high-speed rotating tool with a probe pin is plunged at a specific rate into the overlapping weld spot until contact between the shoulder of the tool and upper workpiece is achieved,

Table 2. Weld appearance in FSW of polyethylene sheets with varying process parameters, adapted from [54].

Rotation speed = 15000 rpm Welding speed = 10 mm/min Pin diameter = 3 mm 	Rotation speed = 15000 rpm Welding speed = 28 mm/min Pin diameter = 3 mm 	Rotation speed = 15000 rpm Welding speed = 44 mm/min Pin diameter = 3 mm 
Rotation speed = 5000 rpm Welding speed = 10 mm/min Pin diameter = 3 mm 	Rotation speed = 5000 rpm Welding speed = 10 mm/min Pin diameter = 1 mm 	

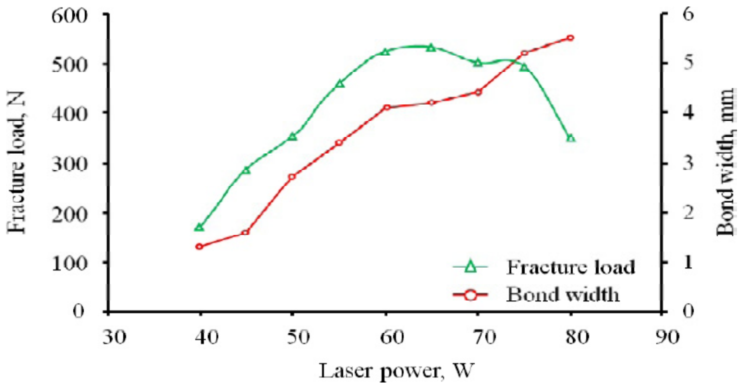


Fig. 9. Relationship between laser power, fracture load, and bond width, replotted from [42].

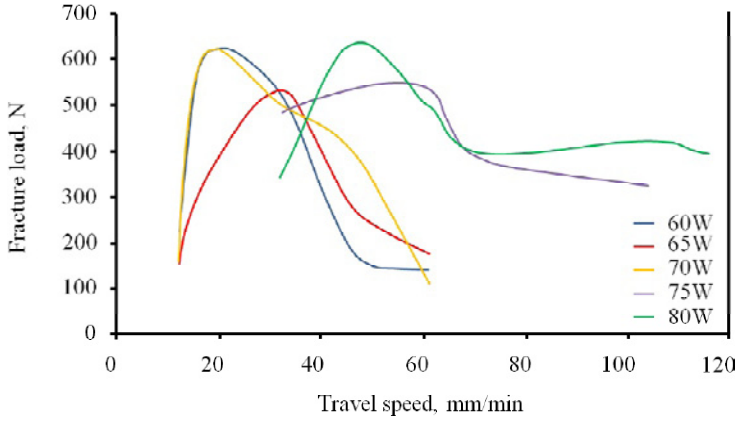


Fig. 10. Relationship between travel speed, fracture load, and laser power, replotted from [42].

which thereby causes material flow as a result of plastic deformation around the pin [44,47-49].

Utilization of the friction spot welding process to produce quality welds with good mechanical properties and keyhole-free surfaces has been feasible in welding dissimilar metals such as aluminum alloy and magnesium alloy [50]. A number of studies have shown that the formation of intermetallic compounds after welding Al and Mg alloys include Al_3Mg_2 [51].

The conventional FSW technique for metals suffers from problems when applied to the welding of plastics [52]. These problems are related to the poor thermal conductivity and diffusion resulting from the macromolecular structure of thermoplastics [53]. Hence, it is difficult to obtain a sound and quality weld in friction stir welding of plastics [54]. To address these problems, rather than a rotating shoulder used in conventional FSW of metals, a special tool fixed with a shoe is necessary to successfully weld thermoplastics [52]. The most important parameter in the FSW of plastics is the machine spindle speed [52], which significantly influences the overall weld quality, as shown in Table 2.

As a variant of the friction spot joining of metals, friction spot joining of metals to polymers incorporates two distinct processes; the sleeve plunge and the pin plunge. The sleeve plunge and pin plunge variants can be applied separately as a single process [55]. In sleeve plunging, the workpieces are initially overlapped and clamped between a backing plate and a clamping ring with the metal part placed on top of the polymer workpiece. The sleeve and pin rotational motion is then initiated, with both pieces rotating in the same direction. At some point, the sleeve touches down on the upper workpiece metal, bringing about frictional heating [55]. Simultaneously, the sleeve is inserted into the metal workpiece, thus plasticizing the metal, and the pin is retracted, which consequently results in the formation of an annular space or reservoir, as shown in Fig. 10A [55]. The plasticized metal is then squeezed into the created reservoir as a result of the sleeve plunging effect. Upon completion of the joining process, the sleeve is retracted from the metallic workpiece surface and the pin extrudes the entrapped plasticized material back into the weld. The keyhole is consequently refilled, as shown in Fig. 10B [55].

Tool plunging is set in such a way that plunging takes place only in the metallic workpiece. This is done to avoid damage to the fiber reinforcement of

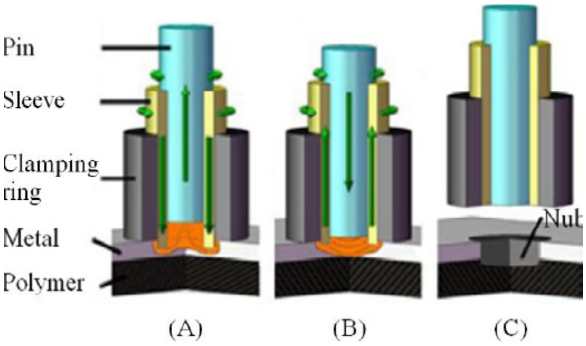


Fig. 11. Schematic presentations of sleeve plunge variants: (A) sleeve plunging and plasticizing of the metallic material; (B) spot refilling; (C) joint consolidation, adapted from [55].

the polymeric workpiece, which can reduce joint strength. The plasticized metallic workpiece is further deformed by the sleeve plunging, resulting in the formation of a metallic nub on the surface of the polymeric workpiece, as shown in Fig. 10C [55]. Frictional heat generated and stored in the metallic workpiece is then transferred by conduction to the polymeric workpiece, which results in the formation of a thin layer of molten/softened polymer beneath the spot surface [55]. Eventually, the sleeve tool joining head is retracted, and the spot weld is consolidated under pressure, as shown in Fig. 10C.

Amancio-Filho et al. [55] investigated the feasibility of friction spot joining in magnesium/fiber-reinforced polymer composite hybrid structures. In their study, a hybrid joint was made between a 2 mm sheet magnesium alloy (AZ31B) and two 8 mm thermoplastic composites (glass fiber and fiber-reinforced polyphenylenesulfide). Prior to the joining process, the AZ31 specimen was ground with a P1200 SiC paper to remove the Mg $(OH)_2$ layer. Both workpieces were cleaned with acetone to remove surface contaminants.

During the joining process, it was observed that unlike the friction spot joining of metals, the energy input in friction spot joining of metal to polymer is a function of the welding parameters. Surface observation and microstructural investigation of the welded joints showed two concentric ring impressions left behind by the tool in the spot area, shown in Figs. 11A and 11C. The internal ring consisted of stirred material, whereas the external ring was the result of the impression left by the clamping ring. The cross-section view of the welded joint showed a plastically deformed metal volume nub inserted into the polymeric workpiece, Fig. 11B. It was concluded that the geometrical features observed enhance the holding force by mechanical interlocking in the direction of shear.

Fracture surface analysis of the PPS/- CF/AZ31 joint in Fig. 12A revealed a mixed cohesive–adhesive type of fracture at the joint interface. In a composite workpiece, a cohesive failure was observed, as can be seen by the partial polymer matrix and fiber attachment on the magnesium plate, shown in Fig. 12A. An adhesive mode of fracture was observed in the polymer–metal interface, seen as black regions on the magnesium plate in Fig. 12B. The occurrence of a partial adhesive failure is evidence of the role of adhesion in joint formation with FSJ.

Amancio-Filho et al. [55] concluded that hybrid metal–polymer joints obtained by friction spot joining achieve greater joint strength than adhesive joining even without surface preparation, as it can be seen in Fig. 13. Furthermore, the joint strength of the metal-to-polymer hybrid joints could be increased by up to 50% by the increasing the surface roughness of the metallic workpiece from 0.75 μm to 3.45 μm.

4. CONCLUSIONS

This paper discussed joining methods for metal-to-metal, polymer-to-polymer and metal-to-polymer hybrid components. Different joining techniques were presented and their advantages and disadvantages

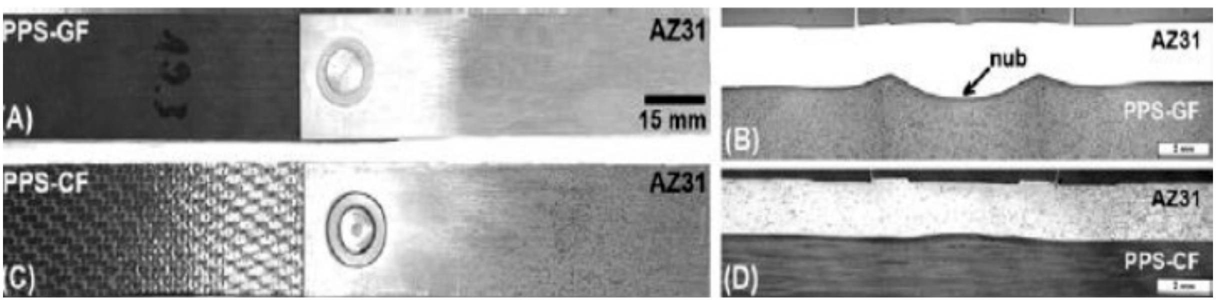


Fig. 12. (A) Surface appearance of PPS/Mg AZ31 single lap joint; (B) optical micrograph of PPS/AZ31 joint; (C) surface appearance of PPS/-CF/Mg AZ31 single lap joint; and (D) cross-section of optical micrograph of PPS-CF/AZ31, adapted from [55].

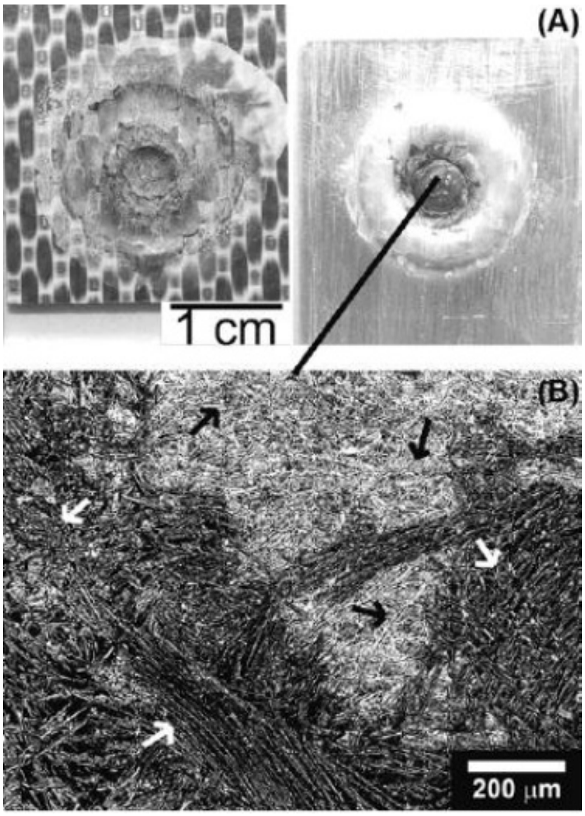


Fig. 13. (A) PPS-CF/AZ31 lap joint view; (B) Microstructure of the joint, adapted from [55].

examined, along with adaptations of the processes. Mechanical joining guarantees a reliable joint and high joint resistance when joining metal and polymer, typically with rivet joining. However, the process has limitations due to poor flexibility in terms of joint design, since the joint shape and position is usually fixed mechanically, and the production rate is therefore relatively slow. Adhesive joining techniques are undoubtedly the most used process for joining plastic to metal. Adhesive joining is a relatively simple technique and high design flexibility can be achieved. However, this joining process suffers several disadvantages, such as relatively low mechanical resistance, a limited working temperature range – as the polymeric adhesive depolymerizes at high service temperatures, low resistance in a chemically reactive environment, difficulty in forecasting long-term durability, and extensive specimen surface preparation requirements.

Of the welding approaches thus far researched, ultrasonic metal-to-polymer welding seems to be a most promising method for hybrid structures when joining metals to polymers, and it has been successfully employed to join metal and fiber-reinforced polymers. This welding method is a solid state joining technique and no microstructural changes occur in the metal. There is uniform mixing between the metallic and polymeric part, which promotes intermolecular contact and mechanical interlocking in the weld zone. High joint strength can be achieved with relatively low energy input and very short welding times.

Friction spot joining presents similar results to ultrasonic metal welding. The joining is achieved in the solid state and also with uniform mixing of the metal and plastic workpieces at the joint interface. However, this joining method has only been successfully applied to low melting point metals such as magnesium and aluminum. One limitation of the technique is that it is mostly suitable for low melting point materials and is not applicable to very thick metals (currently, the tested thicknesses have been within the range 1–2 mm). The main advantages of the friction spot joining process are the availability of commercial welding equipment, short joining cycles, its operational simplicity, and the good mechanical performance of the joints. The feasibility of friction stir welding with metal-to-polymer joints is not fully understood, mainly because of differences between friction stir welding for metals and friction stir welding of plastics. The low thermal conductivity of polymers along with their complex molecular structure requires changes in welding tools and tool design. More studies still need to be conducted in order to understand how the welding method can be controlled.

Laser welding of metals to polymers can be used to achieve stable metallic, chemical, and covalent bonds between metal and polymer hybrid components. It should, however, be noted that bonding occurs in the molten–solid interphase between the plastic and metal as the metal does not melt in this joining process. Rapidly expanding due to high pressure, bubbles are formed in the welding process that enable physical and chemical bonding between the metal and plastic components. High joint strength can be achieved in laser direct metal-to-polymer joining, and this method is applicable to several metals, such as steel titanium, aluminum, and iron. The advantages of this process are very fast welding times, small heat input, and the high adaptability of the process. The limitations of the process are the many parameters, such as travel speed welding power, that influence the quality and reliability of the eventual joint. The joining method also has limited design flexibility and is suitable mainly for lap joints because of the need for effective absorption of the laser beam.

In conclusion, with the exceptions of mechanical fastening and adhesive bonding, all the welding processes, especially those for metal-polymer hybrid components, are still in the developmental stages and more studies need to be done to effectively understand the feasibility and durability of the processes. However, it can be concluded that the new emerging joining techniques for metal-to-polymer hybrid joints are promising and offer alternative methods to traditional techniques for making dissimilar metal-to-polymer joints.

REFERENCES

[[1] A.B. Abibe, S.T. Amancio – Filho, J.F. Dos Santos and E. Jr. Hage // *J. Thermoplast. Compos. Mater.* **24** (2011) 233.

[2] H.E. Friedrich // *J. Adv. Eng. Mater.* **5** (2003) 105.

[3] C.E. Bakis, L.C. Bank, V.L. Brown, E. Cosenza, J.F. Davalos, J.J. Lesko, A. Machida, S.H. Rizkalla and T.C. Triantafillou // *J. Compos. Constr.* **6** (2002) 73.

[4] W.S. Kim, I.I. Yun, J.J. Lee and H.T. Jung // *Int. J. Adhes. Adhes*. **30** (2010) 408.

[5] F. Balle, G. Wagner and D. Eifle // *J. Adv. Eng. Mater.* **11** (2009) 1.

[6] Z. Sun and R. Karppi // *J. Mater. Process. Technol.* **59** (1996) 257.

[7] C. Ageorges and L. Ye // *Composites: Part A* **32** (2001) 1603.

[8] A. Droste, P. Naughton, B. Bowser, J. Rottger, S. Burr, O. Imam, M. Zeitler, T. Heuft and A. Cawley, In: *Bonding & Joining*, *3rd Annual SPE automotive composite conference* (Michigan, 2003).

[9] A. Filho and S.T. Dos Santos // *Polym. Eng. Sci*. **49** (2009) 1461.

[10] M. Sercer and P. Raos, *Joining of plastics and composites, faculty of mechanical engineering and naval architecture, UNESCO-EOLESS sample chapter* (University of Zagreb, Croatia, 2007).

[11] A.V. Pocius, *Adhesion and adhesive technology: an introduction, 2nd edition* (Carl Hanser Gardener Verlag, Munchen, 2002).

[12] K. Hakala and T. Tiainen,In: *The proceedings of structural adhesives in Engineering VI* (Bristol, UK, 2001), p. 143.

[13] R.D. Adams, *Adhesive bonding: science, technology, and applications* (Taylor & Francis, 2005).

[14] L.H. Lee, *Adhesive bonding* (Plenum Press, 1991).

[15] G. Habenicht, *Applied adhesive bonding* (John Wiley & Sons, 2008).

[16] W. Brockmann, P.L. Geiß, J. Klingen and K.B. Schröder, *Adhesive Bonding: Materials, Applications and Technology* (John Wiley & Sons, 2008).

[17] S. Ebnesajjad and C.F. Ebnesajjad, *Surface treatment of materials for adhesion bonding* (William Andrew, 2006).

[18] V.B. Bhandari, *Introduction to machine design* (McGraw–Hill publishing, 2001).

[19] A.F. Grandt, *Material degradation and fatigue in aerospace structures. Air force scientific research. Research initiative on aging aircraft, school of engineering and science* (Purdue University, 1997).

[20] L. Hollaway, *Handbook of polymer composites for engineers* (Woodhead Publishing, 1994).

[21] L. Settineri, E. Atzeni and R. Ippolito // *Int. l J. Mater. Form*. **3** (2010) 995.

[22] S. Chatti, *Production of profiles for lightweight structures* (Books on Demand, 2006).

[23] L.F.M. da Silva, A. Öchsner and R.D. Adams, *Handbook of adhesion technology*, *vol. 2* (Springer, 2011).

[24] H.L. Gower, R.R.G.M. Pieters and I.M. Richardson // *J. Laser Appl*. **18** (2006) 35.

[25] H.L. Gower, *The weldability of metal- polymer hybrid materials* (M.A.Sc, Department of materials science and engineering, Delft University of technology, 2006).

[26] A. Fortunato, G. Cuccolini, A. Ascari, L. Orazi, G. Campana and G. Tani // *Int. J. Mater. Form.* **3** (2010) 1131.

[27] F. W. Billmeyer, *Textbook of polymer science, 2nd ed*. (Wiley-interscience, New York, 1971).

[28] R. W. Cahn and P. Haasen, *Physical metallurgy, fourth revised edition, vol. 1* (Elsevier, 1996).

[29] E.T. Hetrick, J.R. Baer, W. Zhu, L.V. Reatherford, A.J. Grima, D.J. Scholl, D.E. Wilkosz, S. Fatima and S.M. Ward // *Weld J.* **88** (2009) 149.

[30] F. Balle, C. Wagner and D. Eifler // *J. Adv. Eng. Mater.* **38** (2007 934.

[31] S.S. Volkov // *Weld Int.* **27** (2013) 63.

[32] C. Dawes, *Laser welding a practical guide* (Cambridge Publishing England, 1992).

[33] Z. Shusen, Y. Gang, H. Xiuli and H. Yaowu // *J. Mater. Process. Technol*. **212** (2012) 1520.

[34] S. Daqian, C. Xiaolong, D. Peng and G. Xiaoyan // *Optics & Laser Technol*. **45** (2013) 453.
[35] A. Roesner, P. Abels, A. Olowinsky, N. Matsuo and A. Hino, In: *Proceedings of the ICALEO 2008* (ICALEO, 2008), Paper M303, p. 105.
[36] J.G. Drobny, *Handbook of thermoplastic elastomers* (William Andrew, 2007).
[37] G. Buchfink, *The laser as a tool* (Vogel Business Media, 2007).
[38] Y. Niwa, Y. Kawahito, S. Kubota and S. Katayama, In: *Proc. of 26th International Congress on Applications of Lasers & Electro-Optics* (ICALEO, LIA, Orlando, 2007), p. 461.
[39] S. Katayama and Y. Kawahito // *Scripta materialia*l **59** (2008) 1247.
[40] A. Fortunato, G. Cuccolini, A. Ascari, L. Orazi, G. Campana and G. Tani // *Int. J. Mater. Form.* **3** (2010) 1131.
[41] S. Katayama, Y. Kawahiti, Y. Niwa and S. Kubota, In: *Proc. of the 5th LANE 2007 conference* (Erlangen, 2007), p. 41.
[42] W. Tillmann, A. Elrefaey and L. Wojarsk // *Mat.-Wiss.u.Werkstofftech* **10** (2010) 41.
[43] M. Fujimoto, S. Inuzuka and Y.S. Koga, In: *Proceedings of IIW Preassembly Meeting at Nagoya* (Japan, 2004), IIW Doc. III-1296-04.
[44] S. Hirasawa, H. Badarinarayan, K. Okamoto, T. Tomimura and T. Kawanami // *J. Mater. Process. Technol.* **210** (2010) 1455.
[45] T. Iwashita, *Method and apparatus for joining*, US. Patent 6601751 B2 2003.
[46] P. Su, A. Gerlich and T.H. North, *SAE special publication SP-1959* (SAE International, Warrendale, PA, 2005), paper 2005-01-1255.
[47] M.K. Bilici and A.I. YuklerI // *J. Mater. Design* **33** (2012) 545.
[48] S.G. Arul, T. Pan, P.C. Lin, J. Pan, Z. Feng and M.L. Santella, *Microstructures and failure mechanisms of spot friction welds in lap-shear specimens of aluminum 5754 sheets* (SAE Technical Paper 2005-01-1256, 2005).
[49] V.X. Tran and J. Pan // *Int. J. Fatigue* **32** (2010) 1167.
[50] U.F.H. Suhuddin, V. Fisher and J.F. Dos Santos // *Scripta Materialia* **68** (2013) 87.
[51] Y.C. Chen and K. Nakata // *Scripta Materialia* **58** (2008) 433.
[52] W.J. Troughton, *Handbook of plastic joining, second edition* (William Andrew incorporation, 2008).
[53] E.A. Squeo, G. Bruno, A. Guglielmotti and F. Quadrini, *Friction stir welding of polyethylene sheets* (Fascicle V. Technologies in Machine Building, 2009).
[54] A. Mostafapour and E. Azarsa // *Int. J. Phys. Sci.* **7** (2012) 647.
[55] S.T. Amancio-Filho, C. Bueno, J.F. dos Santos, N. Huber and E. Hage // *J. Mater. Sci. Eng.* **528** (2011) 3841.