A REVIEW ON ADVANCED JOINING TECHNIQUES OF MULTI MATERIAL PART MANUFACTURING FOR AUTOMOTIVE INDUSTRY

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Abstract- The use of new techniques and advanced materials is of major interest to automobile and aerospace manufacturing industries for reduce weight, cost and improve part performance. For this purpose, techniques for joining lightweight dissimilar materials, particularly aluminum, steel and plastics are becoming increasingly important in the manufacturing of hybrid structures and components for engineering applications. The choice of proper joining technology is an essential aspect of designing and manufacturing parts. This paper is a review the state of the art in scientific research concerning of joining techniques of dissimilar materials. The review presents the potentials of the technology and chances for further scientific investigations.

Keywords- Dissimilar Material Joining, Mechanical Joining, Clinching, Self-Pierce Riveting, Friction Welding, Laser Welding.

I. INTRODUCTION

Recently, sustainability has been a growing concern for many industries and especially for the transportation sector due to it being the second largest energy consumer and largest contributor of anthropogenic greenhouse gas emissions within the European Union. New legal restrictions on the emission rates have forced the automotive sector to examine different fuel-efficient technologies. Weight reduction is one of the most important methods of improving fuel efficiency and reducing CO2 emissions. Accordingly, lighter, safer, more fuel efficient and environmentally sustainable vehicles are a priority for European authorities [1].

Weight reduction without compromising any safety and performance criteria with reasonable cost is great challenge for automotive industry. Due to car body parts have a huge effect on the total vehicle mass, weight reduction action often focus on the implementation of various lightweight materials aluminum sheets, advanced high-strength steels, magnesium sheets into the automotive body. Therefore a multi material design is often optimal solution. Material selection criteria strongly depend on the cost and manufacturing process [2].

High strength steels (HSS) have great potential in weight reduction. HSS sheets has already been used not only weight reduction of car bodies but also enhance their crashworthiness. Currently, many new types of HSS are being produced by steel manufacturers that have higher strength and ductility, which contribute to weight reduction in the automotive industries. It is expected that efforts to further reduce car body weight by making most effective use of high-strength steel sheet will be continued in the future. However, required stiffness for parts is one of the important criteria. There is a certain limit of lightweighting through the use of thinner steel sheets. If a further weight reduction of 30% or more is called for in the future, it will become necessary to develop and spread out a multi-material structure composed partly of lightweight materials [3].

Materials such as aluminum and magnesium alloys are also allow for reduction of car body weight among which aluminum alloy seems the most promising one due to cost. The European automotive industry has more than doubled the average amount of aluminum used in passenger cars during last decade and will do even more so in the coming years. Its availability in a large variety of semi-finished forms (casting, extrusion and sheet) is main advantage. It makes aluminum very suitable for mass production and innovative solution for compact parts. As well as, it can absorb crash energy two times higher than steel [4].

Using of plastic and composite 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. Advances in manufacturing and forming techniques have also led to increased interest in these non-metal materials for automotive applications. The result is a steady increase of multi-material design and technology in automotive constructions.

Joining processes are an important key factor for the competitiveness of European automotive sector. Vehicles such as aircraft and cars comprise a large number of mechanical parts produced by a variety of manufacturing processes. Cars generally consist of 10,000–30,000 parts, and the number of parts in aircraft is counted in millions. A trend in manufacturing such products is that both the number of parts and their complexity are increasing, including new combinations of dissimilar materials [5].

One of the most important and difficult steps in giving the shape of the multi material car body is the selection and definition of a suitable joining method between two different materials. 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 [6].

Joining of dissimilar materials has been given much attention in recent years due to their superior functional capabilities. Various joining techniques can be used by multi material concept in car designing due to diverse joining and geometrical configurations. One of the most important combinations of dissimilar materials is aluminum with steel due to its potential application in aerospace and automotive manufacturing industries. Despite the many specific benefits, aluminum-steel combination, have a lot of problems like formation of brittle intermetallic compounds, poor wetting behavior of aluminum, difference in physical and chemical properties of the base metals, etc. The melting temperatures of aluminum and steel are quite different. So, conventional fusion welding process does not yield mechanically good joints [7]. There is therefore a need to identify new joining methods for new applications for dissimilar materials.

In the present review, current application of the techniques for joining aluminum alloys, steels and plastics are presented. Especially, the most recent research works on the investigation of the joint techniques which are self-pierce riveting (SPR), clinching, friction stir welding, friction stir spot welding and laser welding are reviewed with the hope that it helps the manufacturing engineers to come up with new ideas.

II. RECENT TECHNOLOGIES FOR JOINING DISSIMILAR MATERIALS

A. Self-Pierce Riveting (SPR) and Clinching Methods

Due to quite different melting temperature, high thermal conductivity, it is not easy to weld aluminum and steel sheets. To solve these problems SPR and clinching process have been developed. In these processes the sheets are mechanically interlocked without metallurgical bonding by controlled plastic deformation. So, the different melting temperatures do not create a difficulty.

In SPR process the sheets are pierced with a tubular rivet, without a pre-drilled hole. The rivet is driven through the upper sheet and the skirt of the rivet is flared in the lower sheet to create an interlock: the lower sheet is hooked on the flared skirt as shown in Fig. 1. Driving the rivet through the upper sheet into the lower sheet and flaring inside the lower sheet is most important rules for successful SPR process. Beside this, fracture in the lower sheet is not desired due to corrosion [5].

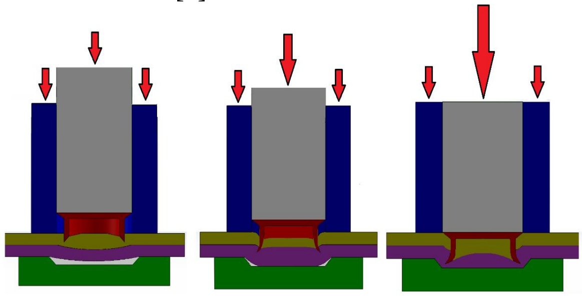

Figure 1. An illustration of sheets by SPR. (a) process start with press force, (b) driving through upper sheet and (c) interlocking

In the mechanical clinching, sheets are joined by local hemming with a punch and die. The joining mechanism is similar to that of self-pierce riveting as shown in Fig 2. The sheets are bulged with the punch, and then compressed with the punch and die. An interlock is formed between the upper and lower sheets by the different amounts of plastic deformation of the two sheets. The most important requirements for successful joining of clinching is avoiding excessive thinning of the upper sheet at the neck of the joint region.

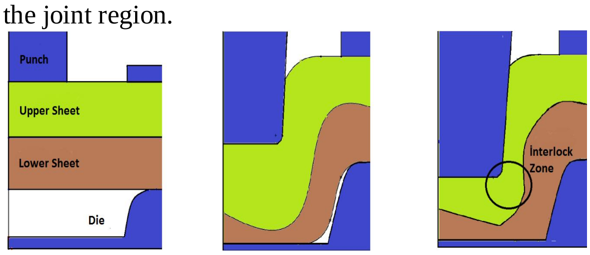

Figure 2. An illustration of mechanical clinching process (a) Initial situation, (b) compression and (c) joining and interlocking

Since the SPR and clinching processes are based on mechanical joining with no metallurgical bonding, the strength characteristic is crucial parameter for the joints. There are many researches about mechanical properties of SPR and clinching process.

Abe et al. with optimized shape of the die, controlled metal flow of the sheets in the mechanical clinching process. Due to small ductility of the high strength steel sheets, they tend to fracture during the clinching process around the corner of the punch. They reported that, the occurrence of fracture induced by the concentration of deformation around the corner of the punch was prevented by decreasing the depth of the die [10].

Mori et al. examined the mechanism of SPR of multiple aluminum alloy and steel sheets. The steel sheets ranged from mild steel to ultra-high strength one having 980 MPa in tensile strength and they investigated joinability for three steel and aluminum alloy sheets for various combinations. They stated that, the optimization of shapes of a die and rivet using finite element simulation is the most effective approach for improving the joinability of self-pierce riveting [11].

Lee et al. developed new process for mechanical joining of steel and aluminum sheets called hole clinching process. In this process, the ductile material is positioned uppermost and the brittle material, into which a hole is formed, is positioned below that. The upper sheet is indented into a die cavity through the hole in the lower sheet and spread so that the two sheets interlock geometrically. They designed special tools for this process and investigated geometrical relationship between the joint strength. They stated that, the hole-clinched joints, regardless of the material combinations, provided a joint strength in excess of the desired 2.5 kN [12].

Gerstmann and Awiszus explained flat clinching and effects of the process parameters. They stated further development of conventional clinching towards hybrid flat-clinching has led to a significant expansion of the technologies' field of application. And also it can be possible to join plastics with this process [13].

Lou et al. proposed a new method for joining aluminum and steel sheets called rivet-welding. This process improved the robustness and strength of the SPR joint by applying an electric current to joining zone. They studied the effects of heating time and electrode design on the microstructure, micro-hardness distribution, and mechanical performance and compared the results conventional SPR process. The results showed that the electric current could improve the microstructure of the steel rivet [14].

Jackel et al. investigated the tool velocity of the SPR process in terms of joining improvements. They stated that with increasing tool velocity, different problems which occurred during tool velocity were below 1 m/s is reduced [15].

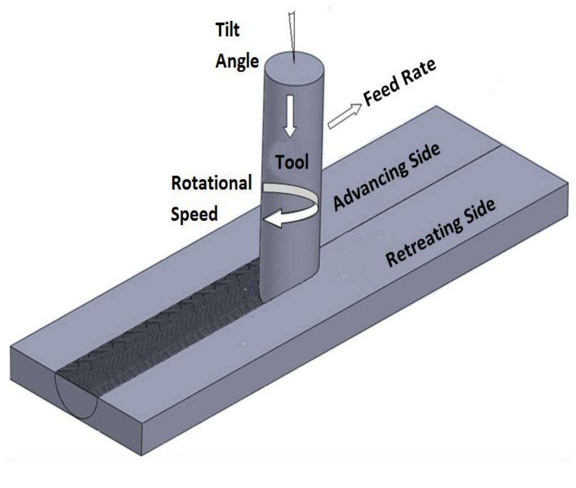

Figure 3. An illustration of friction stir welding process

B. Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) Methods

Friction stir welding (FSW) is a solid-state joining method. It means that no melting occurs during the process. A rotating tool, composed of a pin and a shoulder, is positioned over the future joint and is pushed into the material as shown in Fig 3 [5].

The frictional heat generated by this penetration action softens the work piece material to a plastic condition, making it flow around the pin. Friction stir welding is widely employed in industry for joining especially aluminum alloys.

The FSSW process is a very similar with friction stir welding (FSW). The biggest difference between these processes is movement of welding tool. FSSW process has three phases; plunging, stirring and retracting. First phase of tool is spinning and slowly plunging into a weld spot until the shoulder contacts the upper surface of the work piece. Then in the stirring phase, the materials of the two work pieces mix together. In this phase frictional heat generated and sheets soften. In the last phase when the adequate penetration achieves, the tool retracts from weld area. Fig. 4 shows the phases of FSSW process [16].

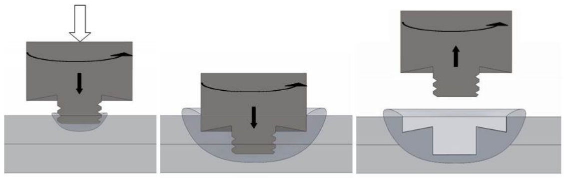

Figure 4. An illustration of the FSSW process: (a) plunging, (b) stirring (Dwell), (c) retracting [16]

FSW and FSSW processes are also applicable to the welding of dissimilar materials and some experiments have been published on joining aluminum to steel. Uzun et al. investigated the microstructure, hardness and fatigue properties of FSW joint of 6013 aluminum alloy to stainless steel. They characterized the microstructures of the weld nugget, the heat affected zone, thermomechanical affected zone and the base materials. The results show that FSR can be used the joining of dissimilar In this study, a good correlation between the hardness distribution and the welding zones are observed [17].

Bozzi et al. investigated intermetallic compounds at the interface of different thickness aluminum-steel and determined as a function of tool penetration and rotational speed. They stated that, intermetallic compounds layer thickness increases with the rotational speed and the penetration depth of the tool [18].

Tran and Pan studied fatigue behavior of FSSW in lap-shear and cross-tension specimens of aluminum sheet and coated steel sheets based on experiments and three-dimensional finite element analyses (FEA). They used FEA results to explain the experimental observations of the fatigue crack growth patterns of the welds [19].

Coelho et al. jointed two different HSS and Al alloy with FSW process and investigated the relations of the microstructure and mechanical properties. They reported that the joint efficiency depends foremost on the mechanical properties of the heat and the thermomechanical affected zone of the aluminum alloy [20].

Liu et al. analyzed the effects of process parameters on the joint microstructure evolution based on mechanical welding force and temperature that have been measured during the welding process. They stated that, welding speed had an insignificant effect on mechanical welding force, temperature distribution and material strain rate. As well as the intermetallic layer composition and thickness reduced with higher welding speed due to shorten high temperature period [21].

Liu et al. developed new method for FSW which called electrically assisted friction stir welding system. This process enables a local electrical current field moving with the FSW tool without requiring the tool to be one of the electrodes. They compared and analyzed mechanical welding force, temperature distribution and microstructure of the joint Al–Fe interface under various process parameters of conventional FSW and electrically assisted FSW process [22].

C. Laser Welding

Laser welding 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. Early studies with laser welding process of aluminum and steel preferred metallurgical reactions between solid phase of steel and liquid form of aluminum by heat conduction between two overlapped sheets. In recent years considerable experiments have been published on joining aluminum to steel with laser welding methods.

Kuadri-David and PMS Team investigated the feasibility of heterogeneous welded joints between DP600 steel and aluminum 6082. They used keyhole welding and laser induced reactive wetting process for getting heterogeneous joints. They reported that, in the keyhole process, joint shear strengths obtained 190 MPa. Compared to the base metal the welded joint shear strengths obtained correspond to 60% that of aluminum and 30% that of DP600 steel [23].

Ma et al. introduced a new welding procedure based on using two-pas laser scans for joining steel to aluminum sheets and obtained completely defect-free galvanized steel to aluminum lap joints. For the evaluating the joint's mechanical properties mechanical testing and micro-hardness test conducted. They stated that, the obtained joints by the two-pass laser welding approach had a higher failure value than those joints obtained when the zinc at the faying surface was mechanically removed under the same welding speed and laser power [24].

Liu et al. carried out a research about laser fusion–brazing of aluminum alloy to galvanized steel with pure Al filler powder and they investigated the effects of the laser power and powder feeding speed on the formation and mechanical properties of the joints. In this research Nd:YAG laser with pure Al filler powder used [25].

Meco et al. developed a process for joining of thick aluminum and steel plates directly without any filler material. For this purpose, they used laser to join steel to aluminum overlap configuration by welding-brazing process. The steel surface is conducted through and melts the aluminum to wet the steel surface [26].

Windmann et al. used laser beam welding for the joining of the sheets of aluminum-coated high-strength steel and aluminum. Inductive preheating of the steel surface investigated with respect to the possibility of improving adhesion. They stated that, weldability of Al-coated and press-hardened high-strength steel could be improved by removing brittle coating particles and dioxides on the steel surface by sandblasting [27].

As the advantages of high strength steel, aluminum alloys and fiber reinforced composites are mentioned above, in order to effectively apply these materials to the component parts of the automobile industry, the development of various manufacturing technologies is required. Especially dissimilar materials joining between non-metal and metal are important and necessary for their widespread applications and an improvement in product functionality and performance. There are several researches in literature.

Jung et al. by used laser-assisted metal and plastic direct joining type (LAMP), joined carbon fiber reinforced plastic (CFRP) and galvanized steel. They used CW diode laser with a line-shaped beam. In order to evaluate the joint possibility and the strengths of CFRP-zinc-coated steel lap joints made by LAMP joining, tensile shear tests were conducted [28].

Tan et al. investigated the mechanism of porosity formation during the laser joining of CFRP and steel sheets [29]. Liu et al. conducted a research about joining aluminum and plastic. They demonstrated friction lap welding (FLW) through a case study on AA6061 and MC Nylon-6. The lap joints with high shear strength were obtained over a wide range of welding parameters [30].

Of the above techniques, adhesive bonding is also widely used in plastic and metal joints. Huang et al. investigated adhesive–embossing hybrid joining process for A2017P and three types of glass-fiber-reinforced plastic (GFRP) thin sheets. They reported this process is a competitive alternative joining method for the fabrication of ultra-lightweight thermosetting GFRP-metal hybrid structures [31]. Di Franco et al. studied an adhesive-rivet hybrid joining method for CFRP and aluminum alloy sheets, and reported that rivet joining could be measured as an effective auxiliary method for increasing the strength of an adhesively bonded joint [32].

III. CHALLENGES

Even though developing rapidly, there are several challenges for multi material joining techniques in Turkey automotive industry. The most important constraint for implementation of the new techniques in mass production is cost and expenses. Cost is a major concern in the automotive industry. It is often the main consideration when choosing a joining technology considering existing equipment. Actually, to minimize investments, equipment is maintained rather than changed. The other constraint is quality of the joint, which are mechanical performance and surface. Developing a joining technique demands to look into quality control possibilities in order to meet product quality as easily as possible without additional process. The last consideration is production cycle and then speed of joining process. in Turk automotive industry, even though some techniques are robot assisted so their speed is adequate, utilizing robot assistance production for other joining techniques must encouraged.

CONCLUSION

Lightweighting is one of the most important goals of the present and especially future automotive industry. For this purpose, multi material car bodies are inevitable and using advanced high strength steel and aluminum alloys in bodies will increase. This paper presented current developments and processes based on the state of research in the literature about dissimilar joining technologies of steel-aluminum joints. This study is a review of related researches to self-pierce riveting, clinching, friction stir welding, friction stir spot welding and laser welding. Among these technologies, laser welding is come to the fore in terms of production rate and surface quality. In multi material car body, one of the challenging and most important part is the joining techniques between these materials. Joining technologies are essential for the realization of innovative and energy-efficient lightweight construction for combining dissimilar materials in multi-material car body designs. Due to variety of materials increase, as well as demand for process reliability, availability, flexibility and cost-efficiency results in a high level of innovation pressure in the field of joining technology.

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