Review of Hybrid Joining Technologies: Classification of the Processes and Advances in Hybridization

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ABSTRACT

Industries which produce structural components have recently shown remarkable interest for the hybrid joining techniques due to their sheer benefits as compared to the fundamental welding methods. The hybrid welding process has vast potential by extending applications of different fields like laser, plasma, arc, and adhesives. As a fringe benefit, it provides considerable advantages like better weld quality and higher efficiency of joints. This study delineates the basic principles, methods and usages of plethora of hybrid joining processes. Various hybrid joining techniques are introduced and their outcomes from vast literature are studied to find the scope of this technology for commercial applications. In every field, to go further for new developments, the literature survey is the very initial step to have a look at different approaches and to select the topic to be studied and investigated. The main argument of this review paper is to understand the latest technologies in the area of hybrid joining techniques, their improved utility in various industrial applications and identification of some areas for further research.

Keywords: Hybridization, joining technique, welding, joint strength, process parameter

1.0 INTRODUCTION

Hybridization of welding processes is usually done to find a hybrid process that combines the best characteristics of each parent welding process, with a hope for some synergistic benefit additionally [1-3]. In hybrid joining, two fundamentally different processes are combined to create a process with extended capability. Hybrid process sometimes may result unique benefits due to synergy between the two basic processes [2]. The main feature of hybridization is to unify the advantages of basic joining techniques and compensate their disadvantages [4]. Hybridization of joining techniques results in various benefits like increased weld speed, lesser thermal stresses, deeper penetration, and lesser need of joint preparation. Improvement in joint strength may be due to higher deposition of welded materials, better molten pool stability, and improvement in metallurgical properties of weldments [1-7].

For an efficient utilization of hybridization, precisely understanding of the complicated physical parameters that govern it and feasibility of their synchronization is must. Coupling of various joining processes like fusion welding techniques, solid state welding techniques, and chemical/ adhesive bonding represents large range of hybrid joining methods [5-8]. A lot of research work has been performed till now in this area. From the survey of this work, efforts are made to find the scope for new developments in the field of hybridization.

2.0 FUNDAMENTALS AND CLASSIFICATION OF HYBRID TECHNIQUES

In the area of joining the work pieces for high quality joints and for better efficiency of the processes, numerous works have been done and large amount of work is still in process. Targets of the research work of this field are to develop a joining technique with higher welding speed with stabilized welding process, reducing the rejection work and minimization of the pre and post welding treatments [4-5]. This study is based on database of large literature from which different approaches of hybridization of joining methods were identified and then their classification was done. We use journals to select a particular topic for new work because it is believed that these are the resources which are mostly used to collect information regarding latest work in the concerned field [1-10]. Welding processes are categorized as fusion and solid state processes. Chemical bonding or adhesive joining is also being used for joining of metals these days and has been proved useful way of joining in some specific circumstances like low temperature application. Addition of this novel method with fusion and solid state welding has shown better results. To make the analysis better, in this review study hybridization is categorized as:

1) Hybridization of fusion welding with another fusion welding
2) Hybridization of fusion welding with solid state welding
3) Hybridization of solid state welding with adhesive joining
4) Hybridization of fusion welding with adhesive joining

2.1. Hybridization of fusion welding with another fusion welding

Fusion welding is a process in which joining of the metal pieces is done by molten metal [5]. A large amount of heat is librated which ensures melting of the base metal or filler metal which after solidification ensures joining of work pieces. Some of the fusion welding processes are arc welding, laser welding, submerged arc welding (SAW), tungsten inert gas welding (TIG), metal inert gas welding (MIG), plasma arc welding etc. Literature study [1-8] reveals that it is possible to join two fusion welding techniques to develop concept of hybridization. Some successful pairs of fusion welding processes are described here.

2.1.1 Laser- Plasma hybrid welding

High production rate and improved weld quality points supported the development of Laser Beam Welding (LBW) in this area and with time it became an important tool for metal joining. High speed welding, lesser heat affected area and hence lesser thermal stresses are some of the advantages of LBW. Major drawback of it is the small bridging capacity. So LBM may be coupled with other processes to compensate it.

Plasma Arc Welding (PAW) was developed as an improved version of the Tungsten Inert Gas (TIG) welding [9]. PAW performed better than LBW as it combines some advantages of LBW, like high concentration of energy, and Metal Arc Welding, like bridging of gap. But the process instability is the main concern of PAW. Hence to overcome their respective drawbacks hybrid welding techniques are developed. Here we study Laser- Plasma hybridization.

Claus E et al. [1] worked on this technique with 4 mm thick Al metal using laser power 550 W, welding speed 30-150 cm/min and gas flow rate of 0-15 l/min. They obtained best results of the work at current (I) = 150 Ampere (A), welding speed = 50 cm/min and gas flow rate (GFR) = 4 l/min and due to focusing effect between plasma and laser, penetration depth was more as compared that of plasma arc welding. F Moller et al. [2] examined this hybridization method for Al alloys and found that laser causes reduction of plasma voltage and this effect decreases with increase in plasma current. They pointed out that plasma voltage effect was more in case of DCEN.

2.1.2 Laser-SAW hybrid welding

Laser has chances of pore formation in the lower weld if is used for deeper welding. Submerged Arc Welding (SAW) process is used for high deposition rate as it is used for joining of plate of thickness up to 15 mm. Sometimes weld quality is not proper as metal penetration is not proper. The hybridization of SAW with laser makes it possible to weld a plate of 20 mm thickness in single pass and that is of high quality. Laser-SAW hybrid welding improves degassing and reduces feasibility of pore formation. This hybridization is illustrated in **Fig. 1**.

Uwe Reisgen et al. [3] worked on X65 steel using laser- SAW welding method. In the experiment laser power was 20 KW and welding speed was 1m/min. They noticed that for reducing porosity it was necessary to separate flux and laser and for it a separating plate was used which is shown in **Fig. 1b**. The results showed hardness of 240 HV on laser dominated area which reduced post weld heat treatment requirement. Average impact energy in Charpy - V test was also high toward laser dominated area and that was 200 J. In another work Uwe Reisgen et al. [4] investigated this hybrid technique with 30 mm thick S235 metal system and obtained fruitful results.

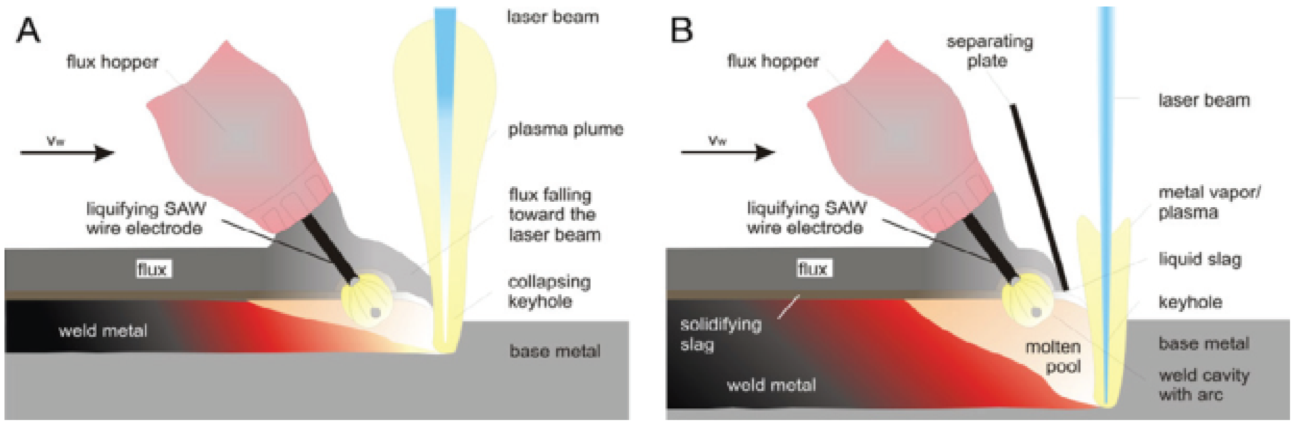

Fig. 1 : (a) Schematic of SAW- laser hybrid welding; (b) Regular process with separating plate [3].

Tensile strength of the joint was equivalent to that of base metal and impact energy in Charpy- V test was higher in laser dominated area as compared to that of SAW dominated area. The lesser impact energy of SAW dominated area was due to coarser grains in this part of weld.

2.1.3 Laser-Arc hybrid welding

Arc welding is a fusion welding process in which arc is developed between the workpiece and electrode which acts as a source of heat and melts the filler metal [5]. It is a commonly used joining process of metals due to simplicity in operation. There are some drawbacks also like, low penetration, poor weld quality at high speed welding. The arc becomes unstable at high speed and it results in an irregular weld. Normally the arc takes the route between the electrode and the work piece having smallest resistance. The hybridization of laser and arc welding processes overcomes some of the above mentioned lacunas. After the mutual interaction in these two processes has taken place, it opens large scope of applications and increases its utility [5, 7]. **Table 1** contains outcomes of laser-arc hybridization works.

2.1.4 Plasma-GMAW hybrid welding

In Gas Metal Arc Welding (GMAW), arc is the source of heat which is created between base metal and filler wire and the filler wire is melted by the arc heat, droplets of metal travel

Table 1 : Summary of hybrid laser- arc welding process journal papers.

Sr. No	Author	Metal/ Filler metal	Parameters	Results
1.	Gang Songa et al. [5]	Mg alloy AZ31B	LP=400W; I=300A; WS=80mm/min	Tensile shear strength was 0.8 times to that of base metal and corrosion resistance of fusion zone was almost equal to that of base metal.
2.	A. Fortunato et al.[6]	304 SS/308L wire	TI=65; GFR=20l/min; WS=1m/min; LP= 3KW	Mutual distance of the two mating sources must be 2-3 mm; focus of laser depends on the metal transfer way of GMAW; Pulsed arc may be used for globular metal transfer.
3.	Xiaoyan Gu et al.[7]	Q235A steel/ H08Mn2Si	GFR=20l/min; WS=5mm/s; LP=.5-1.5KW; I=70-100A	Laser influenced the shape of arc, reduced droplet transfer and resistivity, and stabilized the arc.
4.	Hongyang Wang et al.[8]	AZ31 Mg 6061 + Al alloys	0.08 mm thick Ni interlayer; 0.1 mm thick Adhesive	Ni interlayer restrained the reaction between Mg and Al so there was no intermetallic formation which ultimately increased joint strength.

TI= Torch inclination; GFR= gas flow rate; WS= welding speed; LP= laser power; I= current across the arc and makes weld pool. On the basis of research work it was established that at low currents, metal transfer is not proper and hence some other source is required for heating the droplets of filler metal [9]. In hybrid welding of Plasma-GMAW combination, arc is positioned inside the other arc which is created between plasma nozzle and base material. Both the arcs are placed coaxially. Heat from the outer arc stabilizes the droplet transfer at low currents.

C.H. Kim et al. [9] in their study used Al 5083 plate of 25 mm thickness as base material and Al 5183 wire as filler material. A mixture of 50% helium and 50% argon was supplied. The filler wires diameters were 1.2 mm, 1.6 mm, and 2.4 mm, and power source was DC pulse current. In this process argon was used to act for the shielding, plasma, and GMA gas with corresponding GFR of 5 l/min, 15 l/min, and 10 l/min respectively. Direct current (DC) pulse was used for power source of GMA and a continuous wave current was applied for plasma arc. It was found that in this hybridization method, the surrounding plasma arc was source of additional heat and stabilized the droplets transfer. For a 1.6 mm diameter wire the melting rate in case of plasma-GMA hybrid welding was nearly three times than that for GMA welding.

2.2. Hybridization of fusion welding with solid state welding

Solid state welding is a process of joining in which coalescence of work pieces is obtained at the surfaces by the heat or by the pressure or by both provided that heat generated is below the melting point of the work pieces. Resistance spot welding and friction stir welding are the common varieties of solid state welding. Hybrid joining technique developed by combination of fusion and solid state welding processes has been proved useful which can be seen in the successive literature study.

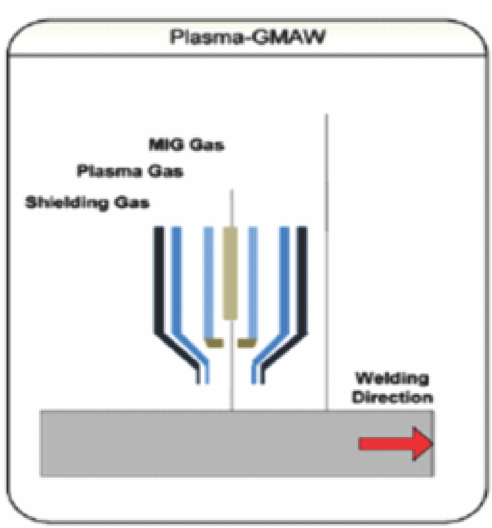

Fig. 2 : Schematic of Plasma- GMAW hybrid joining [9].

2.2.1 Laser- FSW hybrid welding

Friction Stir Welding (FSW) is a solid state joining technique [10] in which there is a rotating tool which plunges into the work piece and generates enough heat by friction between itself and work pieces. Due to this heat plastic deformation takes place and hence joint gets prepared. Originally this process was developed to weld aluminum and its alloys.

The temperatures in this process is lower than the melting point temperature of the job hence the problems found in products of fusion welding, like vaporization of few of the constituents, formation of second phases, porosity, embrittlement cracking, fumes, arc flash, spatter etc. can be eliminated. It also minimizes inclusions and impurities, distortion, residual stresses; and hence the joint exhibits excellent mechanical properties. FSW does not require any filler metal and mostly its operations are without a shielding gas [10-11].

For welding of thicker plates and high melting point alloys, like steels, titanium and nickel alloys, very high heat is desired for softening the work pieces so that the joining can proceed. Due to insufficient heat input, groove like defects get formed in the stir zone, which decreases the quality of weld. Also, the tool faces a risk of being broken as very high resisting force get applied on it during the stirring of hard metals. To overcome these difficulties in working of FSW with high strength metals some additional source of heat may be used. Hence hybridization of FWS with Laser is a useful approach in this direction. There is asymmetry of material flow in advancing and retreating side. Position of laser and distance between the

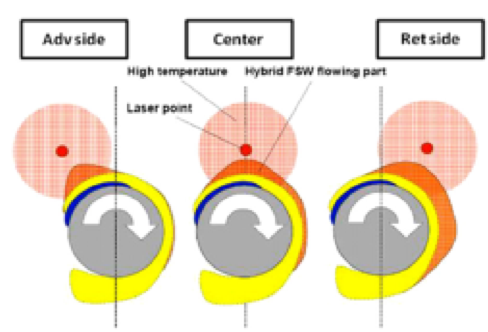

Fig. 3 : Illustration of the positional effect of laser in FSW process (Adv = advancing; Ret = retreating) [12].

Table 2 : Outcomes of hybrid laser- FSW process papers.

Sr. No	Author	Metal/ Filler metal	Parameters	Results
1.	Woong-Seong Chang et al. [11]	AA6061-T6 Al Alloy + AZ31 Mg Alloy	LP=2KW; TS-800 WS=80m/min r/min; WS-35 mm/min; Plunge depth - 3.9 mm; Pin length - 3.8 mm	Max tensile strength was 95 MPa, and 169 MPa (with Ni foil) as there was reduction in formation of inter metallic brittle material at interface with use of Ni foil
2.	Y. F. Sun et al. [12]	Carbon steel S45C plates	LP-2kw; TI-45; TD-15 mm; Shielding gas - Ar	Max speed of welding was 800 mm/min when laser beam was positioned 10 mm before the tool, and laser prevented brittle martensite and bainite formation by preheating of the job

WS= welding speed; LP=laser power; I= current; GFR= gas flow rate; ED= electrode diameter; D= defocus distance; TD= tool diameter; TS= tool speed; TI= torch inclination

Out of the three positions as shown in Figure 3, retreating side fixing of the laser gives maximum material flow [12]. But, if we use high welding speed there are chances of easy tool breakings as friction in advancing side is high. Results of some experiments on laser- FSW hybridization are illustrated in the **Table 2**.

2.2.2 GTAW assisted FSSW hybrid technique

Use of light weight metals like Al and Mg alloys is increasing for structural purposes. So, for Al and steel hybrid structures, adequate welding process is desired. It is tough to get good dissimilar metal joints by fusion welding due to the formation of inter metallic compounds which decreases the mechanical properties of the weld [13].

Being a solid state welding, FSW process reduces chances of inter metallic phase formation in dissimilar metal joining. When FSW is used for joining of dissimilar metals like Al/Fe alloy, Al/Ti and Al/Cu alloy, it is tough to get good joints because of the properties difference in them. So we use another heat source in the form of GTA for equal heat distribution in hybrid friction stir spot weld (HFSSW) [14]. Hansur Bang et al. [14] elaborated this effect in their work using Al alloy (Al6061-T6) + SS (STS304) metal strips of 3 mm thickness. Shoulder diameter of tool was18 mm, probe diameter was 6 mm and pin length was 2.7 mm. The results found that 2 mm from weld center maximum tensile strength was 290 MPa and slightly finer recrystallized grains were in the stirred zone of HFSW than that of FSW.

In another work [14] they used Al6061-T6 Al alloy and 6%Al–4%V Ti alloy of 3.5 mm thickness and found that maximum tensile strength was 300 MPa and microstructure of the HAZ in the Al alloy was very similar to Al alloy base metal.

2.3 Hybridization of solid state welding with adhesive joining

Structural adhesive are used to join the various kind of materials. Although this method of joining has been successfully used in aerospace industries since the mid of 20th century, problems of their long time durability have resulted in limited applications. Exposure to heat or moisture can result significant reduction in bond strength and may lead to its failure. Combination of adhesive with solid state welding processes has resulted in improved strength of the joint. In this hybrid method adhesive provides unique advantages. It changes the input parameters required for the successive solid state welding process.

2.3.1 FSS- Adhesive hybrid welding

Adhesive provides uniform stress distribution in the entire bonding area and weld made by FSW improves the peel resistance of the adhesive joints. S H Chowdhury et al. [15] investigated application of adhesive (Terokal5089 adhesive) with FSSW process. They found that with the use of adhesive, in addition to FSSW, for joining of Al-Mg metal system failure energy was 26.5 J. Also, hardness in the stir zone was uniform with the application of adhesive. **Fig. 4** shows scanning electron micro graphs (SEM) of the fractured surface. From the graphs it is clear that cracks initiated at the interface of Mg and Al.

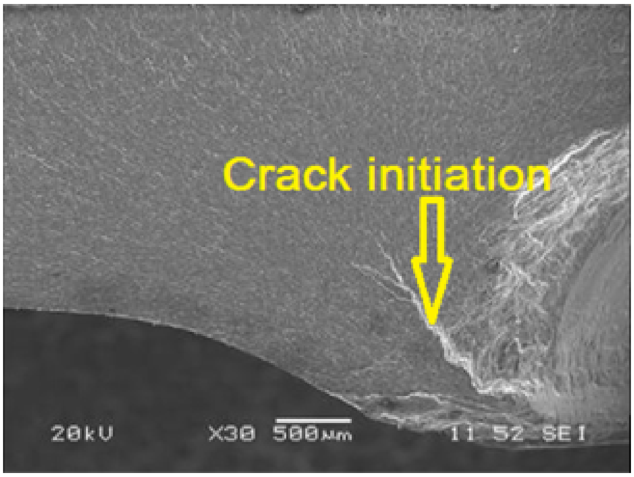

Fig. 4 : SEM analysis of the fractured surface of the dissimilar Al/Mg weld- bond during fatigue test [15].

2.3.2 Resistance spot- Adhesive hybrid welding

Resistance spot welding is a solid state process of joining the metal systems [16]. It is mostly used in automobiles and space industry. So, required strength of the joint is high. So we need to improve the technique. This is achieved by the combination of this process with adhesive bonding. Some researchers have worked in this area and obtained some useful results.

G. P Marques et al. [17] worked with C45E plain carbon steel using Araldite AV 138 and resistance spot welding. They investigated effect of adhesive properties on the joint strength and found that adhesive worked much better and joint strength improvement was 39.1% with Araldite AV 138. In another research Hector R. M Costa et al. [18] worked with IF steel using Syntho-Subsea epoxy adhesive and observed that adhesive thickness was considerable point for proper joint strength. The results indicated that besides contamination of nugget, there was gain in the shear strength of the joint. Micro hardness in the nugget was more than that in heat affected zone (HAZ).

2.4. Hybridization of fusion welding with adhesive joining

Sensitivity of adhesive to temperature makes them difficult to use with fusion welding. But in some cases this combination has proved to be beneficial. Hybridization of adhesive with ultrasonic welding, laser welding, plasma welding, and MIG welding has been done [19-23]. Heat produced in fusion welding can damage adhesive but use of adhesive has benefited the joint strength and process parameters.

2.4.1 UTM- Adhesive hybrid welding

Michele Carboni et al. [19] worked on Al alloy and Mg alloy metal systems by combining ultrasonic welding and adhesive. They found that fatigue and tensile shear behavior of the hybrid lap joint were better than the joints obtained by individual processes. Two kinds of failure were observed.

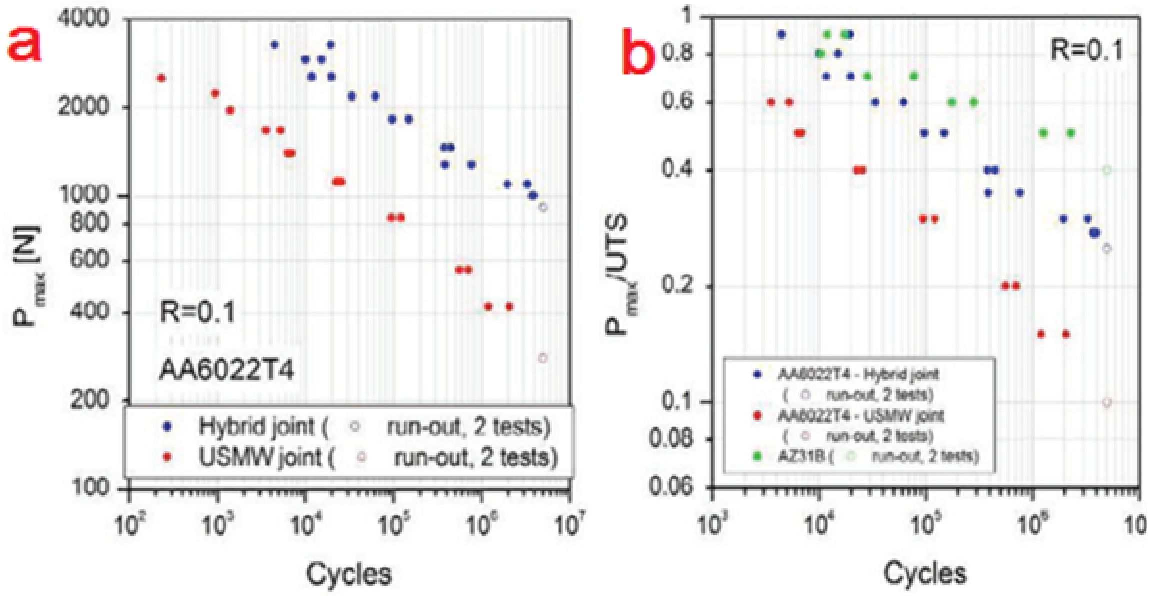

Figure 5. Fatigue S-N curves for (a) 6022-T4 aluminum alloy using USMW process and hybrid process and (b) comparison of S- N curve of 6022- T4 alloy and AZ31B magnesium alloy [19].

From the above figure it is clear that fatigue strength of hybrid weld joint was higher for both kind of metal systems and while compared Al alloy and Mg alloy, Mg alloy showed greater strength.

2.4.2 MIG- Adhesive hybrid joining

Liming Liu et al. [21] experimented on Mg alloy and Al alloy using weld- bond hybrid process of MIG and adhesive. They observed that these metal systems can be successfully joined by this novel process and maximum failure shear strength of the joint was 130 MPa which is about 81% of the strength of base metal. Adhesive used here increased the joint strength due to large bonded part. Peel strength of the hybrid joint was found almost equal to that of MIG spot welded joint.

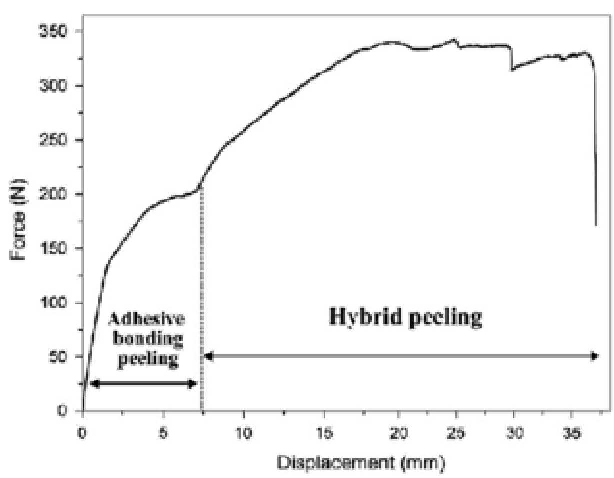

Fig. 6 : Force- displacement relation for MIG- adhesive hybrid joint [21].

In this figure it can be observed that during the peel strength test, it was adhesive which failed initially and weld failed later. Also, weld- bond joint had better peel resistance. Model shown in **Fig. 7** shows that there was recrytalization at the interface of two metals and equiaxed crystals got formed of Mg and Al.

2.4.3 Plasma arc- Adhesive hybrid welding

Jianbo Jiang et al. [20] developed plasma arc- bonding technique for joining of Mg alloy and found that good quality joints could be prepared by this novel method. Adhesive got burnt in welding part and existed in side parts. Joints were free from pores and inclusions. Fusion zone and HAZ had refined equiaxed grains. Smaller grains were found in upper fusion zone in comparison to that of lower zone. They observed that mechanical properties of hybrid joints were better than PAW joint. Failure load for hybrid joint was 6.24 kN and it was 4.46 kN for PAW joint.

2.4.4 Laser- Adhesive hybrid welding

L M Liu et al. [22] worked with laser- adhesive hybrid technique on Mg and Al metal systems. They studied effect of adhesive on micro cracks. Micro cracks were observed by SEM and it was found that out of many cracks in fusion zone, the one in between Al- Mg interface and intermetallic was the main source of joint failure and crack propagation. In case of hybrid joint, adhesive reduced the temperature contrast among eutectic phase and intermetallic and hence tendency of crack formation. It happened because adhesive changed the surface tension of Al alloy. Due to reduction in cracks at interface, tensile shear sample of hybrid joint failed at the edge of joint. SEM analysis of the weld morphology is shown in **Fig. 8a** which shows effect of adhesive on the weld structure and morphology. **Fig. 8b** is SEM analysis of micro cracks which got formed at the interface of Mg and Al.

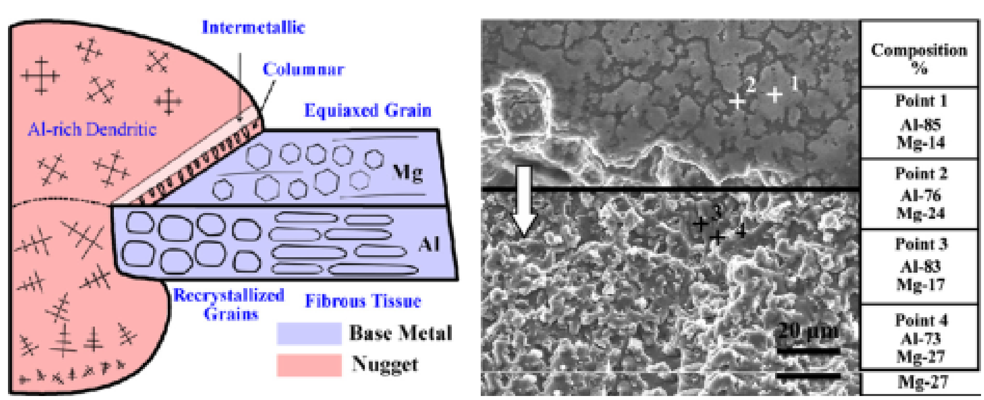

Fig. 7 : (a) Model diagram of microstructure and (b) fractured surface cross-section of joint [21].

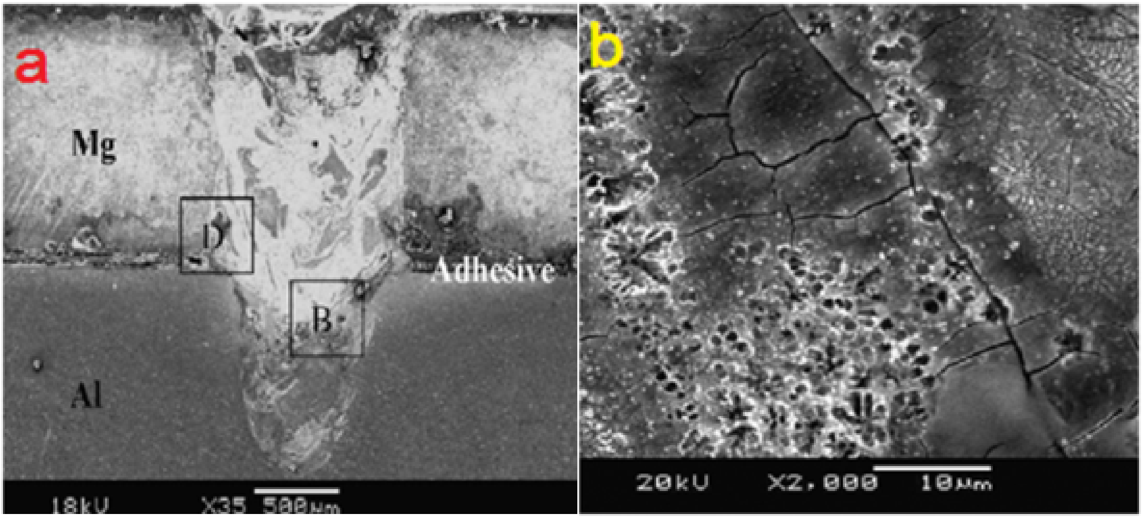

Fig. 8 : SEM of (a) laser weld- bond and (b) micro cracks at MG- Al interface [22].

3.0 RECENT DEVELOPMENTS

With advancement of time, the concept of hybridization has been developed very much. Till now we have studied various phases in this area from the commencement of the concept to huge number of developed processes. The hybrid technique comprising adhesive with solid state joining processes is in developing stage. It has been proved useful to combine resistance spot welding and friction stir spot welding with adhesive for joining the metal system of aluminum alloys. Being a beneficial approach, hybrid welding technique is not used in commercial way and the reason for it is that, effects of process parameters on weld morphology and strength have not been studied. Response surface methodology (RSM) and Taguchi approach has been very useful tool for this purpose [25, 27-35]. Use of these design tools in hybrid joining field is proving useful [24]. These design software are used to study the effect of process parameters on various joint properties like strength etc. We can analysis the parameters' effect on weld individually and in interactive form where we see how two factors effect a response jointly. Also, we get an optimal set of process parameters for which weld performance is best. Hence, with computer application we are proceeding towards applicability of these novel methods in industries. M D Faseeulla Khan et al. [25] used RSM to find out optimal process parameters in the hybrid welding technique of resistance spot weld- bond for aluminum alloy system and found that development of RSM model provided good idea of tensile strength. HanSur Bang et al. [30] worked with Taguchi approach to study the effect of four process parameter of laser-arc hybrid welding technique and found the optimal set of parameters. They noticed that out of welding speed, welding current, laser- arc distance and shielding gas; welding current was the most effective parameter for joint strength.

4.0 FUTURE SCOPE OF WORK

There is no limit of development in any area and improvement in existing methods is always a continuous process. Hence there are many directions in which we can proceed to get better hybrid joining techniques. Some of the feasible areas for future work are as:

1) Till now use of adhesives in hybrid joining techniques is limited only for aluminum alloys and magnesium alloys metal systems, hence it can be investigated for ferrous metal systems which are largely used for structural purposes.
2) Feasibility of adhesives has not been checked with some of the fusion welding processes like TIG, so it may be tested with TIG.
3) To create the confidence regarding durability of the developed hybrid methods, design software may be used for finding the behavior of parameters with joint strength and to get optimal combination of parameters.
4) For a specific metal system we can develop various hybrid joining techniques and then test these processes for desired results. On the basis of their results' comparison, the most efficient hybrid method can be found for that metal system.

5.0 SUMMARY

This study includes the findings from various research journals on hybrid welding processes of different kinds. Each research journal describes some specific hybrid welding process. In this field a lot of research has been done in past and its application is increasing rapidly in automobile and aerospace industries where weight reduction with improvement in efficiency is very must. This field has wide and bright scope for further research. Joining of materials with different metallurgical properties is possible with hybrid welding without any compromise on material properties and weld strength. Also, hybridization of processes improves the weld qualities with slight increase in cost and it gives synergetic result in some cases.

Combination of adhesive bonding with various joining techniques is a vast field. In this paper we studied this hybrid approach in form of laser- adhesive, FSW- adhesive, MIG-adhesive, plasma arc- adhesive etc. From literature survey of these combinations we found some useful results for particular metal systems. Hence some work can be done in this field for other metal systems. Also, feasibility of combination of adhesive with other remaining fusion welding techniques like TIG may be examined as no work has been done in this direction.

The discussion made in the previous sections shows advantages of various hybridization techniques. Combining of two or more joining processes can't be always fruitful. Therefore, it is necessary to check the compatibility of the processes to be combined. The basic purpose of this study was to identify and classify the hybrid joining methods proposed by various researchers. Mostly of the suggested combinations are concerned with specific metal systems. How to determine the feasible combination of fundamental joining techniques is a vital issue of research study. Many of the predecessor studies have provided facts with this point of concern, but further modifications and new areas of hybridization are also possible. A comparative study in detailed manner of the different possible combinations of joining techniques can be carried out. There are some difficulties of adapting the adhesive bonding with fusion welding processes as adhesives are not suitable for high temperature conditions, hence research work can be done to find the limited scope of such combinations. For commercial utility of the hybridization techniques that have been developed theoretically, extended research is required.

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