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Review

# A systematic review on recent progress in advanced joining techniques

# of the lightweight materials

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**Abstract:** We are living in a time where the emphasis is given on the development of new and improved materials having high strength and are correspondingly light in weight for application in fields such as transportation, aerospace, medical and other such related areas. These new materials developed need to be processed and joined with oneself and other materials as well. The paper presents a brief understanding of the advanced joining processes namely friction stir welding, microwave hybrid heating, electron beam welding, laser beam welding, thermo-hydrogenated diffusion bonding, electromagnetic welding and ultra sonic welding. The purpose of these advanced joining techniques is to increase the efficiency of the joining process and prevent failure. The objective of this review paper is to provide an insight into the principles, current trends and research gaps in advanced joining techniques.

**Keywords:** friction stir welding; microwave hybrid heating; electron beam welding; laser beam welding; electromagnetic welding; ultra sonic welding

## 1. Introduction

Joining is the process of combining a broad spectrum of materials using three basic techniques of temporary or permanent fastening, adhesive bonding and welding. Generally, the products which

we use in our daily life are multi-materials because using different materials increases design flexibility and functionality. These give rise to the high demand for materials which are having high tensile strength, light in weight and environmentally inert in fields such as automotive, aerospace, electronics, medical and marine. New and improved alloys of titanium [1–3], aluminum [4,5], nickel [6], copper [7–9] and stainless steel [10–12] are now in use because of the properties they possess which are desirable. Table 1 presents the abundance of elements in earth's crust [13]. Titanium being the ninth most abundant element of earth's crust and fourth most widely available structural element is comparatively lighter than the originally engaged materials such as nickel (Ni), copper (Cu) and stainless steel (SS). The strength of Ti is the same as steel but is less dense than it and has a high melting temperature of about 1670 °C, which makes it functional even at elevated temperatures [14]. Moreover, it has high corrosion resistance, fatigue resistance, crack resistance and biocompatibility. Ti is currently in use in aerospace [15], marine [16] and biomedical [17] industry. Ti can be welded using traditional welding processes such as plasma arc welding [18] and gas tungsten arc welding [19]. These joints formed have low ductility, high residual stresses and easy deformation characteristics [20,21].

Rank	Element	Symbol	Atomic number	Earth's crust abundance
1	Oxygen	0	8	46.60
2	Silicon	Si	14	27.70
3	Aluminum	Al	13	8.13
4	Iron	Fe	26	5.00
5	Calcium	Ca	20	3.63
6	Sodium	Na	11	2.83
7	Magnesium	Mg	12	2.59
8	Potassium	K	19	2.09
9	Titanium	Ti	22	0.44
10	Hydrogen	Н	1	0.14
23	Nickel	Ni	28	0.009

 Table 1. Earth's crust element abundance [13].

Aluminum (Al) is the third most abundant element of the earth's crust and most widely available structural element. The aluminum alloys have high specific strength, corrosion resistance, low density, high conductivity and on top of it, it can easily be processed [22]. These alloys offer high strength to weight ratio in addition to enhanced design adaptability [23]. These advantageous properties have aided it to find applications in aerospace [24], automobile [25], naval [26], weapons [27] and electronics industry. When Al alloys are welded using fusion welding processes it leads to hot cracking, oxide layer formation and poor weld strength because of low molten viscosity, high reflectivity and intrinsic oxide layer formation [28]. Stainless steel (SS) is an iron (Fe) based alloy containing approximately 11% chromium (Cr) and 0.03–1% carbon (C). Common alloying elements include manganese (Mn), nitrogen (N), aluminum (Al), silicon (Si), sulphur (S), titanium (Ti), nickel (Ni), copper (Cu), selenium (Se), niobium (Nb) and molybdenum (Mo) [29]. SS has many desirable characteristics such as excellent mechanical properties, corrosion resistance, ease of maintenance, sustainability and recyclability which can be exploited in aerospace [23], automobile [30] construction [31] and marine [32] applications. SS can be welded using fusion

welding but upon cooling crack propagation of the weld starts which makes post-welding and pre-welding heat treatment compulsory [33].

Inconel is a nickel (Ni) and chromium (Cr) based super alloy, it exhibits superior mechanical properties and corrosion resistance [34]. Owing to these properties it has found applications in aerospace [35], petrochemical [36] and nuclear [37] industry. Products generally which require such material properties also require complex geometries and low tolerance values. Selective laser melting (SLM) is exercised for producing Inconel parts but this technique has a limited working volume [38]. So, to large components, these smaller parts need to be joined together. Due to presence of Laves phase there is a serious defect of micro fissuring or liquation cracking in Inconel welds. The limitations of traditional welding techniques as discussed above cause decreases employability of many metals and alloy which are best suited for an application. To overcome these, advanced joining techniques namely friction stir welding (FSW), microwave hybrid heating (MHH), electron beam welding (EBM), laser beam welding (LBM), thermo-hydrogenated diffusion bonding, electromagnetic welding (EMW) and ultra sonic welding (USW) are utilized. The objective of this review paper is to provide a brief understanding of the advanced joining techniques principle, current trends and research gap for follow on study. Table 2 presents the principle, process parameters, joint configuration and materials processed for various joining techniques.

Technique	Principle	Process parameters	Joint configuration	Materials processed	References
Friction stir welding (FSW)	Welding due to heat generated between work piece and tool because of the rotation, translation motion and mechanical pressure on the tool	Tool geometry, tool offset, rotational spindle speed, translation tool speed, tool tilt angle	Butt joint, T joint	Al/Mg alloys, Al/Cu alloys, Al alloys, Ti alloys, Mg alloys, Ni alloys	[39-47]
Microwave hybrid heating (MHH)	Welding by utilizing microwave radiations and concentrating them at the joining region	Size of susceptor powder, feeder diameter, feeder height, insulation brick thickness, separator thickness, size of interface powder, exposure time	Butt joint	Mild steel, stainless steel, Ni alloys, MS/SS, Al alloys, Cu	[48–56]
Electron beam welding (EBW)	Kinetic energy of electrons is utilized to melt and join the work piece together	Welding speed, beam oscillation pattern, beam offset, input voltage	Butt joint, corner joint, T joint	Ni alloys, Ti alloys, Al–Cu–Li alloys, stainless steel, SS/Cu alloy, Fe/Al alloys, Ni/stainless steel	[57–66]

**Table 2.** The principle, process parameters, joint configuration and materials processed for different advanced joining techniques.

Continued on next page

Technique	Principle	Process parameters	Joint configuration	Materials processed	References
Laser beam welding (LBW)	LASER is employed to convert is light energy to heat energy for melting and joining the work piece	Input voltage, welding speed, focal position, clamp pressure, oscillation radius, oscillation frequency	Butt joint, lap joint, T joint	Stainless steel/ABS, NiTishape alloys, Al/plastic, plastic, stainless steel/plastic, Ti/plastic, Al alloys	[67–76]
Thermo hydrogenated diffusion bonding	Solid state joining under high temperature and pressure in which one/both of the base materials are hydrogenated before bonding	Hydrogen weight percentage, bonding temperature, holding time, clamp pressure, heating rate	Lap joint	SS/Ti alloys, Ti alloys, Ti/Ni alloys	[77–85]
Electromagnetic welding (EMW)	Employing electromagnetic fore to weld the work piece similar to explosive welding	Current frequency, input voltage, standoff distance	Lap joint	SS/Al alloy, Al alloys, Al/Cu, Al/Mg alloys, Al/metallic glass, Al/carbon steel	[86–94]
Ultrasonic welding (USW)	Welding takes place due to the mechanical force and the oscillating force between the sonotrode and work piece	Ultrasonic power, welding pressure, interlayer thickness, welding time	Butt joint, lap joint	Al alloys, Al/stainless steel, Al/Cu, steel alloy, stainless steel, AlMg <sub>3</sub> /composite, Al/Ti alloys, composite	[95–104]

#### 2. Friction stir welding

Thomas et al. [105] developed this technique of friction stir welding (FSW) back in 1990 for joining low-temperature material such as Al alloys while working at Welding Institute and has been termed as the most promising welding technique. In FSW, a non-consumable tool having a pin and a shoulder is engaged, the shoulder of the tool rides along the surface and generate a large fraction of the total heat as it is rotating. The pin penetrates the material shorter than the depth of the material. The heat generated by the rotation, translational motion and the mechanical pressure on the tool causes the localized heating of the interface which softens the material and locally forges the work piece without melting it.

Singh et al. [41] studied the FSW of Al–Mg Alloys and observed that proper selection of the tool geometry improves the material flow behavior. They concluded that threaded pin enhances the joint efficiency, the cooling system enhances the joint reliability and post weld heat treatment (PWHT) improves the weld grain structure. This is due to the reason that the pin geometry is one of the key parameter in friction stir welding. The addition of threads and flutes increase the

area of the pin which in turn increases the heat input to the joint, thus producing a defect free joint. The cooling of the weld helps in fabricating ultrafine grain joints because it produces the flow stress conditions required for plastic deformation of the material by limiting the temperature. As the rate of cooling increases the weld nugget zone decreases.

Hou et al. [106] investigated the role of tool offset in FSW of Al and Cu under optimized process parameters and observed that the tool offset influenced surface quality of the joint and the peak temperature which increases as the tool offset decreased. A large offset of more than 1.6 mm gave poor weld and maximum UTS of 152 MPa was achieved at 1.2 mm. Hasan et al. [107] compared five different tools for the influence of machine variables and tool profile on the tensile strength of dissimilar AA7075–AA6061 and observed that tapered threaded and flat pins resulted in weld having high tensile strength and good surface finish whereas smooth cylindrical pins gave lower joint strength. Aali [108] studied the role of spindle rotation rate on FSW of Ti<sub>4</sub>Al<sub>2</sub>V alloy and concluded that as the rotational speed increases the hardness of the weld zone increase and also found that for achieving optimal weld properties, coordination between transverse speed and rotational speed should be maintained.

Shah et al. [43] experimented with the tool tilt angle on FSW of Al alloys and concluded that the tool tilt angle influences the mode of fracture of the weld and the 2° tilt angle gave highest tensile strength of the weld. Sun et al. [45] investigated the mechanical properties of butt joints of AZ61 Mg alloy and found that the ratio of transverse speed to rotational of 3 provided average joint efficiency of 100.8%. Malopheyev et al. [44] studied the FSW 6061-T6 Al alloy and found increasing the welding speed stalled the precipitation coarsening, improving the macro-scale uniformity which enabled the recovery of the weld strength. Speed of 760 mm/min established the joint efficiency of yield strength of 93% and post-weld heat treatment completely recovers the weld strength. Costa et al. [42] compared the per meter cost of FSW and resistance seam welding (RSW) and concluded that FSW was more economical than RSW of thin Al sheets. Sato et al. [46] investigated the effect of microstructure of Inconel 600 alloy using polycrystalline boron nitride (PCBN) tool in FSW and found that weld had better mechanical properties than the base metal. Song et al. [47] studied the FSW of Inconel 625 alloy and established that FSW preceded to grain refinement thus improving mechanical properties as compared to the base material. Li et al. [109] fabricated successfully the defect free additive and non-additive T Joints using shoulder FSW. The fatigue fracture was determined by the stress concentration. The process parameters of FSW such as transverse speed, rotational speed, axial force, tool tilt angle and tool offset are important in producing a high strength weld, therefore selection criteria should be generalized for these process parameters.

#### 3. Microwave hybrid heating

Microwave hybrid heating (MHH) is an advance joining process utilizing electromagnetic radiations of wavelength varying from 1 m to 1 mm and frequency between 300 MHz and 300 GHz for different wavelengths for joining materials [110–112]. The insulation brick has a cavity to hold the work piece and the refractory brick has a hole drilled for the susceptor powder which absorbs the electromagnetic radiations and concentrates them over the joining region. A graphite sheet is used as a separator to prevent the mixing of susceptor material and work piece. Localized selective heating, low power consumption, decreased sintering temperature and being environment friendly pave the way for its promising future.

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Gamit et al. [48] postulated that susceptor powder was the most crucial factor in heating and melting of the work piece and, as the size of the powder decreases energy transfer to the work piece increases. Kumar et al. [54] studied the MHH of SS without using filler material and established that due to the uniform volumetric heating the joint exhibited homogenous microstructure. After the hardness testing, it was found that the joint region was harder than the base material because of absorption of carbon from the graphite sheet. Sharma et al. [49] investigated the process parameter in MHH of Inconel 625 alloy and concluded that diameter of the feeder was the most significant factor (among insulation brick thickness, separator thickness and feeder diameter) as it directly affects the separator sheet thickness. Gupta et al. [55] studied the MHH of mild steel (MS) and SS using Ni as an interface material and successfully obtained a fine microstructure of the joint and a proper fusion of the material of the took place. Bagha et al. [50] joined SS304 using Ni as an interface material of the took place. Bagha et al. [50] successfully is soft which produced the best results. Correspondingly, found that as the size of Ni powder decreased hardness of the weld increased but ductility of the weld was compromised. Singh et al. [56] successfully joined Al alloy plates with MHH using an Al slurry which melted to form a homogenous dense joint.

Pal et al. [52] optimized the MHH process of joining SS304-SS304, SS304-SS316 and SS316–SS316 using Taguchi Philosophy. Here, three different sizes of Ni powder and three different processing times were used. Srinath et al. [113] compared the simulation and experimental results of MHH of bulk copper and found that they were in good qualitative and quantitative agreement. Badiger et al. [51] optimized the parameters for MHH of Inconel 625 and obtained higher values of tensile strength using graphite separator, SiC susceptor and a fine filler powder. The ANOVA results concluded that the particle size of the interface was the most significant parameter followed by separator and susceptor material. Samyal et al. [53] predicted the exposure time of SS using MHH by fixing some parameters which affected the exposure time and joint strength. They also established a relation between the refractory bricks and specimen dimensions which also influenced the vertical-cavity dimension. Bhoi et al. [114] studied susceptor material for MHH and postulated that for low temperature application susceptor assisted crucible for suitable, charcoal was appropriate for a temperature range of 500-600 °C and SiC should be used for high temperature applications. Lingappa et al. [115] investigated the bulk melting of non-ferrous materials such as Tin, Zinc, Al and brass and from the time temperature curve of the material concluded that the rate of temperature increase is linear up to critical temperature and shoots up rapidly as microwave starts coupling with bulk material.

Due to the inadequate understanding of microwave interaction with different materials, this joining technique is limited to only a few materials. There is an increasing requirement to study this phenomenon with advanced materials and optimizing the process parameters and developing mathematical relations between the parameters and the work piece of similar/dissimilar material.

## 4. Electron beam welding

Electron Beam Welding (EBM) was developed by a German physicist Karl-Heinz in 1958 and is one of the most promising joining technique because of its high quality of the weld and deep penetration [116]. EBW is a liquid state welding process using an electron's kinetic energy to fuse the work piece. A jet of high-velocity electrons strikes the work piece thus, converting the kinetic energy to heat energy which melts the work piece and fuse them. The EBW setup is enclosed in a vacuum chamber. A power source is used to supply a continuous beam on electron; its power rating depends upon the thickness of the weld. The electron gun is the most crucial component of the setup, which is a cathode tube generating and accelerating the electrons. The purpose of the anode tube is to attract and focus these electrons onto a fixed spot and a series of magnetic lenses helps intensifying the electron beam by absorbing low energy divergent electrons.

Richards et al. [57] studied the influence of EBW parameters on heat affected zone (HAZ) micro fissuring in Inconel 903 and found that lower welding speed and high current for a particular heat input significantly reduces micro fissuring. In electron beam machining, as the welding speed decreases and current input increases large amount of energy is transferred to the weld material in a substantial amount of time which results in low rate of temperature rise and leads to shallower cooling rate. As the solidification time increases, it allows more time for the temperature gradient to fall off and low welding speed produces shallower temperature gradients whereas in case of high welding speed there is a steep temperature gradient. When more time is allotted for the temperature gradient to drop off in the heat affected zone, the maximum thermal stress and rate of extension on liquid film decline which in turn decreases the tendency of heat affected zone micro fissuring.

Iltaf et al. [60] compared three oscillating patterns of EBW of Ti5Al2.5Sn and concluded that the arrow pattern had higher hardness than elliptical and concentric circle pattern, whereas they had higher ductility and notch toughness due to the presence of  $\beta$  phase in greater amount and uniform microstructure respectively. Peng et al. [64] experimentally investigated the mechanical properties and microstructure of EBW of Inconel 718 and discovered the grain size in the HAZ gradually decreased from top to bottom of 12 mm thick Inconel 718 plate. Zhang et al. [66] systematically investigated and optimized the process parameters for EBW of Al–Cu–Li alloy and developed an inverse relation between weld porosity and heat input. As the porosity decreased the mechanical properties were increased. Singh et al. [63] compared the low and high heat input in EBW of 2205 duplex SS and found fine grain microstructure in lower heat input weld. Higher micro hardness than the base material was revealed in both the case. Impact toughness was significantly reduced in the weld as well as the base material.

Zhang et al. [58] employed EBW for welding of 304 SS to QCr0.8 Cu alloy using a Cu filler wire and postulated that the beam current was significant factor followed by welding speed, wire feed rate and beam offset. Dinda et al. [61] studied the EBW of carbon steel and Fe–Al alloy under different weld conditions. It was revealed that the oscillating beam resulted in uniform and homogenous microstructure and subsequently increasing the welding speed promoted fine-grain growth. Guo et al. [62] successfully welded Ti<sub>6</sub>Al<sub>4</sub>V and T<sub>2</sub>Cu using EBW, which initially resulted in poor weldability but as the electron beam was shifted to Cu side with an offset of 1.4 mm the strength of the weld increased and subsequently increasing the offset increased the strength but also increased brittleness due to the thickening of the intermetallic compound layer. Sharma et al. [65] investigated the effect of EBW on the properties of Inconel 718 and found significant microstructure refinement and no modification in the corrosion properties. Derakhshi et al. [59] addressed the EBW of Inconel 617 and AISI310, initially, the weld was weaker in corrosion resistance than parent material but as the welding speed increased the corrosion-resistant behavior of the weld improved. Emphasis is given on EBW of Inconel super alloys but certain serious defects such as liquation cracking (micro fissuring) and fusion zone cracking exist in the weld owing to the presence of Laves phase.

#### 5. Laser beam welding

Light amplification by stimulated emission of radiation (LASER) is a highly intense, direction monochromatic radiation. Laser beam welding (LBW) employs LASER for generating a concentrated heat source for deep penetration of the base material. LBW is a clean welding technique converting heat energy in light energy for joining similar/dissimilar materials [117]. In most practical cases, Nd:YAG crystal is used as for fabricating solid state lasers. Yttrium aluminium garnet (YAG) is doped with triply ionized neodymium, Nd (III). Only a fraction of the host material is doped with Nd. Nd provide the same effect as Cr in ruby crystals. Generally the active medium for producing laser used is glass or crystalline material which is doped with rare earth elements in most case such as neodymium, chromium, erbium, thulium or ytterbium because their excitation levels can be easily achieved [67,68].

Noh et al. [70] optimized the process parameters for joining SS304 and acrylonitrile butadiene styrene (ABS) to process stronger welds. Results from ANOVA concluded welding speed has the maximum effect on the weld followed by laser power. Mehrpouya et al. [75] reviewed the LBW of NiTi shape memory alloy and found cracking in the weld zone which could be treated using stress 236 relieving but in significantly degraded the shape memory effect. PWHT was found to be an effective process retrieving the shape memory effect and improving mechanical properties. The PWHT of NiTi shape memory alloy was extensively discussed by Oliveira et al. [118] to recover and improve the properties of NiTi alloys. The paper also presented a detailed review of joining processes of NiTi in similar and dissimilar combinations considering both fusion and solid-state processes and LBW of NiTi was discussed in detail. Bideskan et al. [71] optimized the process parameters for joining of PMMA and AL 6061-T6 laminates and concluded that the focal position followed by laser power has the significant effect on lap shear strength and weld seam width. It was also established that the increase in laser power and an intermediate value of welding speed and focal position produced strong joint. Hao et al. [73] optimized the process parameters for welding of PET and via beam oscillation to produce homogeneous welds without thermal degradation and lack of fusion and shear force was increased by 26% of the sample without beam oscillation. Sayyad et al. [119] studied the effect of laser pre-treatment of Al before LBW of it to polyamide assemblies 6.6 (PA6.6) and concluded that pre-treatment has a strong influence on the weld shear strength.

Amend et al. [120] reviewed the LBW of PC–Al and PA–Alhybrids and found it to be a suitable solution for joining of metal-polymer hybrid components. Katayama et al. [76] successfully welded SS304 and PET sheets using LBW producing strong joints. Chen et al. [121] investigated the effect of ultrasound on LBW of PET and Ti and concluded that the joint formed using ultrasonic aid produced joints having higher ultimate tensile strength than the joints formed without ultrasonic aid. Liu et al. [72] studied the high-speed laser lap joining of Al and polymer with the welding speed of 5m/min fabricating good quality and strong joints which was attributed to the formation of C–O–Al bonds. Shangren et al. [74] experimentally investigated the effect beam oscillation on the LBW of Al alloy and concluded that weld depth and porosity significantly decreased as the frequency of oscillation and diameter increased. It was established oscillation can refine the grain structure and increase tensile strength of weld. Xiao et al. [122] reviewed the LBW of Al–Li alloys and only a reliable weld was formed with decreased mechanical strength and poor ductility.

Al-Li alloys are a suitable candidate for replacing Al alloys in aerospace application due to

more favorable properties. The LBW of Al–Li alloys show poor ductility, material vaporization, bad weld formation and defects such as keyhole porosity and undercut. There is a need to study the reasons behind these limitations of LBW in Al–Li alloy. Optimizing the process parameters and analyzing the effect of filler material and pre/post-weld treatment will be beneficial.

### 6. Hydrogenated diffusion welding

Diffusion welding (DW) is a traditional solid-state joining process in which similar/dissimilar materials are welded together to a form single product under the application of high temperature and mechanical pressure. When DW was employed to weld Ti alloys and Ni alloys the joint strength was highly affected by the formation of the intermetallic formed. The effect of different interface layers was studied on DW of Ti and Ni alloys such as Cu [123], Ni/Ti [124] and silver [125]. Most favorable and viable results were yielded when one/both of the specimens were hydrogenated in a furnace or the interlayer material can be hydrogenated.For hydrogenating the sample it is first heated in a furnace up to the transformation temperature and then cooled in a hydrogen atmosphere. The concentration of hydrogen is controlled by controlling the charging time and the actual concentration is measured by weighing the sample before and after the process. This hydrogenation of sample improves diffusion bonding by improving plastic deformation and diffusion ability of metal materials. Zhang et al. [77] experimentally investigated the Hydrogenated DW of TC4-0.3 H/Nb/GH3128 and found that as the bonding temperature increased the void gradually decreased and disappeared at 860 °C and when TC4-0.3H/GH3128 couples were bonded using Nb/Ni foil the weak (Ni,Cr)ss layer was completely eliminated from the interface.

Zhu et al. [78] studied the diffusion bonding (DB) of weaker Ti<sub>6</sub>Al<sub>4</sub>V and Ti<sub>2</sub>AlNb alloy which had a large mismatch of hot strength and addition of hydrogen (H) further widens the gap. The solution found was to employ a fast heating rate to inhibit H depletion and oxidation before onset DB. The DW of the alloys can be done by hydrogenating both of them to 0.2% wt H followed by fast heating and dwelling. Shanthala et al. [83] compared the DW of hydrogenated and un-hydrogenated CP Ti with SS and found that the joint at with hydrogenated CP Ti can be made plausible at a relatively lower temperature than the other. Wang et al. [79] studied the DW of TiAl and Ti<sub>2</sub>AlNb with hydrogenated Nb foil as interlayer material and compared it with employing pure Nb foil as interlayer and found that the former contained fewer defects and thicker diffusion layer than the latter. As the hydrogen content increased the bonding temperature, thickness and shear strength improved significantly.

He et al. [82] investigated the DW of TiAl and Ni super alloys with hydrogenated Ti<sub>6</sub>Al<sub>4</sub>V interlayer and compared it's results with no interlayer material and former produced a joint having high shear strength than the latter and the parameters significantly decreased. In the hydrogenated interlayer process, faster heating was more favorable than slow cooling. He et al. [84] compared the results direct DW of TiAl and using Ti<sub>6</sub>Al<sub>4</sub>V interlayer the welding parameters decreased and shear strength increased. Feng et al. [80] studied the effect of hydrogen on DW of hydrogenated Ti<sub>6</sub>Al<sub>4</sub>V alloys and observed that the void at the interface decreased as the bonding temperature increased and found faster cooling rate more favorable as it prevented the escape of H and oxidation of the joint surface thus improving bond quality.

Wu et al. [81] experimentally investigated the effect of hydrogen on DW of Ti55 alloy and concluded that as the hydrogen content increased from 0.3 to 0.5% wt the bonding ratio and shear

strength increased due to grain refinement and increase in the volume fraction of  $\beta$  phase. Wang et al. [85] fabricated a strong weld of TC4 alloy using DW with hydrogenated Zr interlayer and compared the results with pure Zr interlayer and found that the thickness of the diffusion layer and shear strength increased remarkably in the former and subsequently the activation energy was also reduced. The processing temperature was significantly reduced with hydrogen addition.

Almost all of the research is based on Ti alloy hydrogenated up to 0.4 wt% which produced similar results. Different materials can also be investigated as work piece and interlayer materials for utilizing the true potential of this technique.

#### 7. Electromagnetic welding

Electromagnetic welding (EMW) is a high speed, solid-state joining process practiced to join similar/dissimilar materials [90]. As this technique mainly employs electromagnetic forces to join materials its application is limited to conductive material only. Faraday's Law states that when a conductive material is loaded with a time-variant current it produces a magnetic field and induces a current in the neighboring conducting object, and Lenz's Law states that the current induced always opposes its origin and produces a magnetic field in the opposite direction [126]. Based on these two laws the principle of EMW is based. Lorenz force is generated by a repelling magnetic field due to the current which is used to accelerate one/both of the work pieces towards each other and produce a joint with strong metallurgical structure. This bonding is similar to explosive welding [127].

In EMW, a high voltage source is required which charges the capacitor to a predetermined value and current flows through the primary coil, inducing a secondary current in the flyer plate. Owing to the current, a magnetic force is produced in the coil and flyer plate which accelerates it towards the target plate and colliding with it, thus, producing a bond at the interface of the two work pieces.

Shanthala et al. [83] investigated the EMW of Al 6061 and SS304, which produced a strong weld without any intermetallic layers. The results of the Helium Leak Test indicated a tight weld between the two. Wang et al. [128] successfully produced robust welds of Al and Cu using EMW. Only a narrow area of the base metals was affected by the EMW in the vicinity of the joint and during the shear test the base material was fractured rather than the joint. The discharge voltage was directly proportional to the interfacial diffusion layer and mechanical interlocking. Li et al. [129] compared different current frequencies of EMW of Al and Cu keeping the discharge energy constant at 10 kJ. The frequencies investigated were 23.1, 17.8 and 15.2 kHz. The current frequency of 23.1 kHz had the shortest time from the deformation of the Al plate to the generation of the jet. With the current frequency of 17.8 kHz the length of the metallurgical bonding zone was the longest which produced the best welding effects. Chen et al. [90] studied the effect of discharge voltage on the weld joint interface of Al alloy and Mg alloy. It was found that the average thickness of the interface layer was exponentially increased from 2.1 to 26 µm as the voltage increased from 4 to 5 kV. The interfacial waves became more regular and smooth as the voltage increased. Kore et al. [86] optimized the process parameters in EMW of Al sheets and its effects were reported. The parameters studied were energy, standoff distance and coil geometry. Raoelison et al. [92] studied the effect of process parameters on the weld produced by EMW and concluded that the air gap had a more significant effect on the weld than the charging voltage. At the low gap, the required velocity was not reached which can damage the flyer and a large gap caused interfacial shearing and material tearing which fabricated brittle welds. Raoelison et al. [130] compared the weld joint of Al-Cu with Al-Al

formed using EMW and observed intermetallic layer in the former and continuous metal bonding in the latter. The Al–Cu weld showed a brittle behavior whereas, the Al–Al welds showed a ductile one.

Watanabe et al. [94] experimentally investigated the EMW of Al-metallic glass lap joints and fabricated sound weld with very little damage to the metallic glass. No change in chemical composition and micro hardness of the base material was observed in 2 µm area of the weld. This is due to the reason that in case of joining Al and metallic glass using electromagnetic welding it was observed that in the Al side the area of 2  $\mu$ m and away had a constant hardness value similar to that of the base material. But the hardness value increased noticeably within the area of 2 µm from the interface because of the grain refinement and work hardening. Xu et al. [91] simulated and test the effect of impacted velocity on EMW of Al tubes. It was found that the impact velocity of the inner and outer tube increased with the increase in voltage. As the impact velocity was greater than 200 m/s, the joint strength was more than base Al strength and as it increased 355 m/s a regular waviness pattern was found at the joint transition region. Lueg-Althoff et al. [93] successfully joined thin-walled Al-Cu tubes employing EMW without using supporting inserts. Deformation in the parent material was found but the weld was achieved. It was also found that Polyurethane inserts significantly reduced the parent deformation and it can easily be removed afterwards. Yu et al. [131] experimentally investigate the EMW off Al-Carbon steel tubes with a pre-set angle and achieved reliable joints. It was found that micro hardness of the base material increased at the interface and the highest value existed in the transition zone.

Most of the research is established on a very narrow range of material and that too with similar parameters. There is to need to check the viability of this process on different material shapes and sizes. Further research on the optimization of process parameters, material behavior and coil design will be beneficial.

#### 8. Ultrasonic welding

Ultrasonic welding (USW) is a non-consumable joining process used to weld similar/dissimilar materials with large melting point differenceand also large differences in mechanical properties. It can be employed to weld plastics and most of the metals. The USW setup is fundamentally an assembly of four components namely ultrasonic generator, transducer, booster and horn. The purpose of the ultrasonic generator is to increase the voltage and frequency of the electrical signal. The transducer converts the electrical signal into ultrasonic waves and vice-versa. Ultrasonic horn also referred to as tool holder, concentrator or sonotrode, it is integrated into the setup to enhance the amplitude of ultrasonic vibration. The material for the horn ranges from Al for ordinary applications and Ti for high-pressure complex applications. Booster is an optional constituent which installed between the transducer and the horn and is used to alter the amplitude of the horn [98]. The welding takes place due to two main forces, a mechanical force to the work piece and an oscillating force between the sonotrode and the work piece interface. The combination of these two forces deforms the work piece and welds them together.

Shah et al. [132] compared the results of USW of AA6061 with conventional resistance spot welding (RSW) and found that higher mechanical strength, ductility, stiffness and energy absorbed before failure in former as compared to the latter. Owing to the ultrasonic vibrations the porosity defects were also significantly removed. Pati et al. [101] studied the effect of thickness of interlayer on USW of Al–SS joints using a zinc (Zn) interlayer and concluded that as the thickness increased,

tensile shear strength increased to 0.11 mm after which it suddenly decreased. Mechanical properties of the composite materials can be evaluated by employing the finite element analysis [133–138]. Li et al. [100] experimentally investigated the effect of pressure on USW of Al–Cu and concluded that as the pressure increased the average vibrational amplitude decreased and thickness of the intermetallic compounds first increased then decreased. At a welding pressure of 1775 N cracking started at base material below the tip of the sonotrode. As the pressure increases brittle joints are found and ductile-brittle fracture under pressure ranges from 1375 to 2175 N. Shah et al. [139] compared the result of USW of TRIP780 Steel with RSW, the welds in the former showed higher joint strength with nugget pull-out failure whereas, the latter failed in interfacial debonding mode. HAZ was found to be wider in USW.

Tsujino et al. [140] successfully fabricated butt welds of Al–SS and SS–SS using USW and found that the joint had the same strength as the base material and hardness of the base material increased due to ultrasonic vibrations. Tsujino et al. [103] successfully joined Al sheets of 0.3–1.0 mm thickness and quartz thin plates a semiconductor tips using complex vibrations USW. The bond strength was proportionally influenced by input energy per real contact area. Jeng et al. [99] investigated the effects of different parameters on the ultrasonic wire welding mechanism and concluded that the weldable range increases as the applied load or the power decreased. Kruger et al. [104] successfully joined PA12/E-Glass composite and AlMg3sheet using pure Al interlayer material without significant damage the fiber glass but strength was lower than ultrasonic metal welding technique. Wang et al. [141] successfully fabricated sound welds of Al/Ti alloys with Al interlayer using USW and found the micro hardness value gradually increased from Al to Ti side. The shear strength attained a maximum value with respect to the thickness of interlayer and remained constant as the thickness increased.

Zhou et al. [102] experimentally investigated the effect of welding time of USW of 1.5 mm thick AA6061 and 1 mm thick commercially pure Ti. It was concluded that welding time affects appearance, microstructure, thermal cycle and mechanical properties. No significant interface layers were generated or intermetallic compounds were created. As the welding time increased the peak temperature achieved a maximum value then constant at 365.6 °C. The failure occurred due to failure of the interface. Kumar et al. [142] investigated the USW GF/PA6T composite of fabricated weld having high strength. It was found that as the welding time increased the void formation gradually decreased which helped produced stronger welds.

USW has a wide range of benefit from mechanical properties, surface quality, and uniform grain growth to reducing the overall cost of the product. But there is still a need to study ductile materials such as Ti, Ni alloys and effects all the parameters, optimizing them, morphology study of weld joints and USW of hard and complex materials.

#### 9. Unique points of the present study

The unique points of the present study are summarized as follows:

 Most of the work which has already been published focuses on a single joining technique and based on earlier research developments. In this review paper, the emphasis has been given to the latest research work on lightweight materials which cannot be joined using traditional joining techniques.

- This review paper aims to provide a brief understanding of the advanced joining processes namely friction stir welding, microwave hybrid heating, electron beam welding, laser beam welding, thermo-hydrogenated diffusion bonding, electromagnetic welding and ultrasonic welding.
- Difficulties of joining of alloys of titanium, aluminum, copper, nickel, etc. has been discussed providing a scope these advance joining techniques has been established.
- Research gaps for the techniques have been discussed individually such as optimizing the parameters, developing mathematical relations between parameter and work piece, investigating different weld configuration other than butt and lap joint and studying the effect of different pre/post-weld treatment of the work piece to increase the joint strength and prevent failure.

## **10.** Conclusions

Throughout history, we have seen the rising need for high strength, lightweight, corrosion resistance and economical materials. Materials were developed, are developing and will be evolved according to our needs. Properties of alloys of titanium, aluminum, copper, nickel, stainless steel and other materials were enhanced to fulfill our desire. Smaller components of these alloys can be manufactured using techniques like additive manufacturing and selective laser melting, but for producing larger components these smaller parts need to be joined together but the traditional joining techniques are not found to be fruitful. Advanced joining techniques like friction stir welding, microwave hybrid heating, electron beam welding, laser beam welding, thermo-hydrogenated diffusion bonding, electromagnetic welding and ultra sonic welding were developed to join together these materials. Though these techniques are found to be beneficial in many cases most of the research was conducted on a narrow range of materials and that too on identical parameters. There is a need to utilize the true potential of these techniques by further exploration and generalizing them, optimizing the parameters, developing mathematical relations between parameter and work piece, investigating different weld configuration other than butt and lap joint and studying the effect of different pre/post-weld treatment of the work piece to increase the joint strength and prevent failure.

## **Conflict of interest**

All authors declare no conflicts of interest in this paper.

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