Recent research progress in solid state friction-stir welding of aluminium–magnesium alloys: a critical review

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Abstract

At present aluminium-magnesium alloys are widely used in various engineering applications due to their light weight and superior properties. Joining is considered as one of the most complex phenomenon in various precision industries like aerospace, railway, automotive and marine structures because inflexible tolerances are required during different product assembly. The friction stir welding (FSW) of aluminium-magnesium of various grade has incited substantial scientific and industrial importance since it has a potency to transform the product with a good quality joint. The fabrication of such alloys is a challenging task through conventional fusion welding due to its various metallurgical concerns. Therefore, the present work is intended to summarize the recent progress in FSW of aluminium-magnesium alloys. Particular attention has been paid to microstructural evolution, phase transformation, recrystallization mechanism, material flow behaviour and how the process parameters influence the various mechanical properties and associated defects during FSW. Various experimental and numerical simulation results have been mentioned for weld property comparison. Finally, this work not only points out the prominent conclusions of the preceding research but also recommends the upcoming guidance concerning to fabrication of aluminium-magnesium alloys through FSW.

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1. Introduction

Nowadays a large demand for lightweight, fuel-efficient and low emissive structures has been fulfilled by the extensive application of aluminium and magnesium alloys (Al-Mg alloys) [1]. The application of both Al and Mg alloys provides a better design adaptability as well as improved strength to weight ratio [2]. The fabrication of dissimilar metals and non-metals has been described as a great importance in materials fabrication techniques, for example, Steel-Mg, Steel-Al and Al-Mg for weight saving and Al-Cu for electrical and electronics circuit connections [3]. Permanent welding and joining has always been an outstanding technique as compare to other fastening methods such as mechanical fasteners and other semi-joining process. Aluminium has some unique properties, such as low molten viscosity, high reflectivity and inherent oxide layer formation which lead to hot cracking and poor joining with conventional laser and other fusion welding [4]. Therefore, friction stir welding (FSW) has been chosen to improve weld quality with its unique processing methods. Various laser welding and other hybrid joining techniques have been tried for dissimilar welding but the FSW has shown best result with respect to joint strength [5–12]. The FSW process has a potential to weld dissimilar materials efficiently due to low temperature generation. Moreover, it is a continuous, hot shear, autogenously process containing non-consumable rotating tool with high hardness property comparing to the base material [13].

The fabrication of several materials through FSW include: (i) Al alloys [14–18], (ii) Cu alloys [19–21], (iii) Mg alloys [22–24], (iv) Ti alloys [25–27], (v) Steels [28–30], (vi) Ni alloys [31,32], (vii) Polymer and metal matrix composites [33,34], (viii) dissimilar metals and non-metal alloys [35,36] and, (ix) dissimilar bulk metallic glasses and metals [37,38].

Most of the metals and alloys are weldable by several methods [14]; however, challenging situations appear when it comes to dissimilar welding especially Al-Mg alloys due to various metallurgical issues. Aluminium and magnesium alloys are much interesting and frequently demanded in various industries, such as automotive, aerospace and marine sectors due to their higher specific strength and lower density to weight ratio value [15,39].

This has triggered out a substantial research progress towards dissimilar metal joining. The sense of dissimilar joining in FSW can be defined in many ways such as: (i) same workpiece material but varying its thicknesses (ii) the same material alloys family with different grade and composition (e.g. Al-6061, Al-7075 and AZ31, AZ21 etc.) (iii) dissimilar metals joining having materials compatibility or solid phase miscibility such as Al-Cu alloys (iv) joining of incompatible metals or immiscible in solid phase such as steel-Mg and; (v) joining of materials having no solubility but potential to form metallic bonds in solid-phase such as ceramic and metal [6,39,40]. In modern automobile body structures a high strength steels can be used in the longitudinal beams for
strength, aluminium alloys in bumper beams for lightweight and to withstand a crash while composite sheets are used in panels for lightweight and high stiffness. In Fig. 1 (a), it is clearly shown that how mass can be reduced by using multi-material such as; aluminium, steel, and magnesium as well as glass fibre reinforced thermoplastics. Fig. 1 (b), it is shown the fluctuations in price of magnesium and aluminium since in decade of 2000 to 2014. It is clear that variation in magnesium price was more as compare to aluminium price [41,42]. These reasonable prices for magnesium has been spur the massive use of magnesium and aluminium together in automotive industries. The use of magnesium alloys in high volume vehicles is a major difficulty due to its high cost. In the USA, prime Mg wholesales at a spot price of around $2.15/pound which is approximately double the of prime Al spot price and considerably more expensive as various other steel sources [42].

There are several advantages and applications proposed by dissimilar material joining through FSW technique like; higher energy saving, cost reduction and competence to ‘tailor’ the materials design in the specific field [43]. Such specialities have been used in the automobile sector by stamping the different types of sheet metal body frames, generally known as tailor-welded blanks [16–18,44]. Moreover, various advancements in dissimilar FSW techniques have explored the new scope for many industries, such as aircraft engine, turbines automotive, X-ray equipment components and nuclear reactor materials [15,40].

In the same context, multi-material products demand for aluminium and magnesium has been increasing continuously. Independently, both metals are used widely in aerospace and automotive engineering due to its numerous advantages, containing high specific strength, light weight and recyclability. However, few specific advantages may consider Al (for higher tensile strength and creep resistance), and Mg (for higher damping capacity) and hence, these properties are utilized at one place to get the benefit of both. Dissimilar material welding through FSW provides a new horizon to utilize the advantages of both materials at a place [45,46].

Dissimilar material joining by FSW characteristics are affected by various set of working parameters namely; welding speed, tool eccentricity, tool rotational speed, and work-piece positions (advancing or retreating side) [47,48]. However,
major difficulties for Al-Mg joining are the development of intermetallic compounds (IMCs) and liquation formation which shows a detrimental effect on weld mechanical properties [49]. As of now, three foremost methods have been addressed in the literatures to overcome these issues, namely; using solid state welding to avoid higher temperatures, control of heat input, and variation in chemical reaction mechanism at joint interface [40,45,49]. Therefore, FSW has been a better option in welding to overcome the formation of IMCs due to its inherent solid-state joining property by maintaining the higher heat input. In FSW technique, non-consumable tool typically comprises of two major parts; shoulder and pin, which can be seen in Fig. 2 [50].

Owing to its increasing adoptability in various industries, this research work highlights the current trends and issues associated with FSW of Al-Mg dissimilar joining. The basic dissimilar FSW tool-sample arrangement is shown in Fig. 3 [51].

The scope of this paper is not only limited to butt joint configuration but also includes various other configuration reported in the literatures. This review paper is carried out by examining the sufficient number of reputed research articles in various aspects especially for Al-Mg dissimilar FSW joining. The broad area which has been covered namely: the heat generation and basic joining mechanism, followed by the mechanical and microstructural properties. Also, the paper has critically assessed the influence of FSW process parameters, associated defects, various applications and suggesting significant considerations for upcoming research.

2. Research progress in dissimilar FSW of Al–Mg

Application of various Al and Mg grade are need to be highlighted such as; Al grade of 2xxx, 5xxx and 6xxx series is popular for commercial use, while, in Mg series, AZ31 is the most commonly used alloy [39,43,45,52]. These lightweight materials are extensively used in aerospace and automobile industries, because of its excellent properties [53]. The various parameters and its consequences on joints are summarized in Table 1.

Table 1 – Major FSW constraints [54–56].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Significant contribution &amp; effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>“Stirring action”, frictional heat, plastic deformation and soft material intermixing</td>
</tr>
<tr>
<td>Traverse speed</td>
<td>Material and heat flow behaviour, weld appearance</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>Bond formation, forging or stirring action</td>
</tr>
<tr>
<td>Tool offset</td>
<td>Optimally distribution of heat and stresses during dissimilar FSW</td>
</tr>
<tr>
<td>Downward force</td>
<td>Maintaining the contact between tool and workpiece, fraction of frictional heat sharing</td>
</tr>
</tbody>
</table>

Table 2 highlights the current trends and research summary of Al–Mg alloys joining through FSW presented in a chronological order, since 2002. The above conclusions are carefully revealed the influence of FSW working parameters namely; traverse speed, rotating speed, tool configuration, tool tilt angle, tool offset and workpiece position. Therefore, in order to achieve the best result in terms of joint strength in FSW of Al-Mg dissimilar welding, a set of appropriate process parameters are required [40,91]. However, to understand the parametric effect on weld quality, it is important to identify the fundamental characteristics of heat input and bond formation mechanisms involved in FSW of Al–Mg alloys. These issues have been addressed in the following subsections in detail.

3. Joining mechanism of dissimilar Al–Mg during FSW

The FSW weld strength is mainly laid on two phenomenon, that is; the weld bond formation due to the existence of IMCs (e.g. Mg17Al12 and Mg2Al3), and; the mechanical interlocking by continuous material deformation. The IMCs formation and its growth are controlled by the local diffusion, rather than the eutectic reaction of Al and Mg atoms. The tensile strength of weld decreases notably with the increase in IMC layer thickness [22,67,92,93]. Table 3 contains the comparison of various physical properties of pure Mg, Al and iron (Fe) [7,45]. It can be seen from Table 3 that by using aluminium and magnesium alloys it can offer potential weight reduction as compared to cast iron and steel. The mechanical and metallurgical properties are addressed below.

3.1. Incompatibility issues during FSW of dissimilar Al–Mg

It is necessary to understand the proper welding phenomena i.e. metallurgical and incompatibility issues during joining of Al-Mg through FSW. The main issue is solubility limitation between aluminium and magnesium in solid-solid phase therefore, it forms the IMCs. The binary equilibrium phase diagram of Al-Mg system is shown in the Fig. 4 [94]. In general, the
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Authors (Year)</th>
<th>Material used (Mg-Al alloys)</th>
<th>Remarks/findings</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Park et al. (2002)</td>
<td>AZ31 &amp; AI050</td>
<td>Preliminary study and defect-free joining by FSW of Al-Mg alloy.</td>
<td>[23]</td>
</tr>
<tr>
<td>2</td>
<td>Hirano et al. (2003)</td>
<td>AZ31 &amp; AI050</td>
<td>Intermixing two phases at the intermediate layer. The formation of IMCs in SZ is restricted.</td>
<td>[24]</td>
</tr>
<tr>
<td>3</td>
<td>McLean et al. (2003)</td>
<td>AZ31B &amp; AA5083</td>
<td>Formation of a very thin IMC layer, results in virtually no ductility.</td>
<td>[57]</td>
</tr>
<tr>
<td>4</td>
<td>Sato et al. (2004)</td>
<td>AZ31 &amp; AI050</td>
<td>The IMC Al12Mg17 was formed by constitutional liquation FSW.</td>
<td>[35]</td>
</tr>
<tr>
<td>5</td>
<td>Somasekharan et al. (2004)</td>
<td>6061-T6 - AZ91D &amp; AZ31B-H24</td>
<td>Lamellar shear bands were seen in either side of Al or Mg.</td>
<td>[58]</td>
</tr>
<tr>
<td>6</td>
<td>Yan et al. (2005)</td>
<td>AZ31 &amp; 1060</td>
<td>IMCs like Al12Mg17 and Al13Mg2 cause the cracking during FSW.</td>
<td>[59]</td>
</tr>
<tr>
<td>7</td>
<td>Zettler et al. (2006)</td>
<td>AZ31 &amp; AI6040</td>
<td>Attained 80% weld efficiency of base material (AZ31).</td>
<td>[60]</td>
</tr>
<tr>
<td>8</td>
<td>Khodir et al. (2007)</td>
<td>2024-T3 &amp; AZ31</td>
<td>Variation in hardness value over SZ due to IMCs formation.</td>
<td>[61]</td>
</tr>
<tr>
<td>9</td>
<td>Morishige et al. (2008)</td>
<td>AZ31B &amp; A5052-H</td>
<td>The SZ hardness was lower than the laser welding fusion zone.</td>
<td>[62]</td>
</tr>
<tr>
<td>10</td>
<td>Kwon et al. (2008)</td>
<td>AZ31B-O &amp; A5052P-O</td>
<td>The tensile strength of 132 MPa was achieved at 1000 rpm.</td>
<td>[63]</td>
</tr>
<tr>
<td>11</td>
<td>Shigematsu et al. (2009)</td>
<td>AZ31B-O &amp; A5052P-O</td>
<td>Maximum tensile strength of 143 MPa was achieved at 1400 rpm.</td>
<td>[16]</td>
</tr>
<tr>
<td>12</td>
<td>Kostka et al. (2009)</td>
<td>AZ31 &amp; AA6040</td>
<td>Observed 1μm thick IMC of fine-grained Al12Mg17.</td>
<td>[64]</td>
</tr>
<tr>
<td>13</td>
<td>Liu et al. (2009)</td>
<td>AZ31B-H24 &amp; 2024-T3</td>
<td>Showing galvanic corrosion due to the Al-Mg galvanic couples growth.</td>
<td>[65]</td>
</tr>
<tr>
<td>14</td>
<td>Firouzdor and Kou (2009)</td>
<td>AZ31 &amp; AA6061</td>
<td>Material positioning directly affects the heat input during FSW.</td>
<td>[66]</td>
</tr>
<tr>
<td>15</td>
<td>Yamamoto et al. (2009)</td>
<td>AZ31B &amp; A5083</td>
<td>Tensile strength of 115 MPa and IMCs Al12Mg17 &amp; Al13Mg2 were achieved.</td>
<td>[67]</td>
</tr>
<tr>
<td>16</td>
<td>Yan et al. (2010)</td>
<td>AZ31 &amp; A5052</td>
<td>Maximum hardness was obtained twice the base metals.</td>
<td>[68]</td>
</tr>
<tr>
<td>17</td>
<td>Firouzdor and Kou (2010a)</td>
<td>AZ31B-H24 &amp; 6061-T6</td>
<td>Formation constitutional liquation was perceived.</td>
<td>[69]</td>
</tr>
<tr>
<td>18</td>
<td>Firouzdor and Kou (2010b)</td>
<td>AZ31B-H24 &amp; 6061-T6</td>
<td>Base metals Positioning affects the IMCs formation.</td>
<td>[3]</td>
</tr>
<tr>
<td>19</td>
<td>Chang et al. (2011)</td>
<td>AZ31 &amp; AA6061-T6</td>
<td>Improved the tensile strength to 66% of base Mg by Hybrid laser-FSW.</td>
<td>[70]</td>
</tr>
<tr>
<td>20</td>
<td>Malavizhi and Balasubramaniam (2012)</td>
<td>AZ31B &amp; AA6061</td>
<td>Influence of tool shoulder diameter (heat generation) on Mg-Al weldment quality.</td>
<td>[71]</td>
</tr>
<tr>
<td>21</td>
<td>Simioneni et al. (2012)</td>
<td>AZ31 &amp; AA5754</td>
<td>Influence of FSW constraints and tool shape.</td>
<td>[72]</td>
</tr>
<tr>
<td>22</td>
<td>Moft et al. (2012)</td>
<td>AZ31C-O &amp; 5083</td>
<td>Water cooling effect on maximum temperature and IMCs formation.</td>
<td>[73]</td>
</tr>
<tr>
<td>23</td>
<td>Venkateswaran and Reynolds (2012)</td>
<td>AZ31B &amp; 6063</td>
<td>Showing relationship between weld interface and tensile strength.</td>
<td>[74]</td>
</tr>
<tr>
<td>24</td>
<td>Pourahmad et al. (2013)</td>
<td>Pure Mg &amp; AA6063</td>
<td>Material flow analysis and IMCs development by steel shots.</td>
<td>[75]</td>
</tr>
<tr>
<td>25</td>
<td>Liang et al. (2013)</td>
<td>Mg &amp; AA6061</td>
<td>Influence of tool rotatory speed and tool offset on weld properties.</td>
<td>[76]</td>
</tr>
<tr>
<td>26</td>
<td>Lee et al. (2014)</td>
<td>AZ31B&amp;AA6061-T6</td>
<td>Observation of plane orientation and fine grains in SZ.</td>
<td>[77]</td>
</tr>
<tr>
<td>27</td>
<td>Sadeesh (2014)</td>
<td>AA2024 &amp; AA6061</td>
<td>The tensile strength of 194 Mpa and 209 Mpa were attained.</td>
<td>[78]</td>
</tr>
<tr>
<td>28</td>
<td>Masoudian et al. (2014)</td>
<td>AZ31-O &amp; AA6061-T6</td>
<td>Maximum tensile strength of 76% and 60% of Mg and Al respectively was achieved.</td>
<td>[79]</td>
</tr>
<tr>
<td>29</td>
<td>Regev et al. (2014)</td>
<td>AZ31 &amp; AA6061</td>
<td>Consideration of peak temperature plasticity over creep analysis.</td>
<td>[80]</td>
</tr>
<tr>
<td>30</td>
<td>Fu et al. (2015)</td>
<td>AZ31B-O &amp; 6061-T6</td>
<td>Maximum tensile strength achieved 70% of base metal (Mg).</td>
<td>[81]</td>
</tr>
<tr>
<td>31</td>
<td>Zhao et al. (2015)</td>
<td>AZ31 &amp; AA6013</td>
<td>Maximum tensile strength obtained 152.3 MPa through UFSW.</td>
<td>[82]</td>
</tr>
<tr>
<td>32</td>
<td>Azizieh et al. (2016)</td>
<td>AZ31 &amp; AA1100</td>
<td>Maximum tensile strength of 122 MPa was achieved of base metal.</td>
<td>[83]</td>
</tr>
<tr>
<td>33</td>
<td>Champagne III et al. (2016)</td>
<td>ZE41A &amp; AA6061</td>
<td>Hybrid joint obtained using FSW and cold spray.</td>
<td>[84]</td>
</tr>
</tbody>
</table>
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Sr. No.</th>
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</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>Zhao et al. (2016)</td>
<td>AZ31 &amp; AA6013</td>
<td>Maximum tensile strength obtained of 152.3 MPa using UFSW.</td>
<td>[85]</td>
</tr>
<tr>
<td>35</td>
<td>Jagesvar Verma et al. (2017)</td>
<td>AZ31B &amp; AA6061</td>
<td>Good corrosion resistance at lower welding speed and high rpm.</td>
<td>[86]</td>
</tr>
<tr>
<td>36</td>
<td>Shi et al. (2017)</td>
<td>Lab-prepared Mg &amp; AA6061-T6</td>
<td>Tailoring of banded structure to enhance the weld strength.</td>
<td>[87]</td>
</tr>
<tr>
<td>37</td>
<td>Xueqi et al. (2018)</td>
<td>AZ31B &amp; AA 6061-T4</td>
<td>Ultrasonic assisted FSW enhanced the Mg to Al alloy.</td>
<td>[6]</td>
</tr>
<tr>
<td>38</td>
<td>Xiangchen et al. (2018)</td>
<td>AZ31B &amp; 6061-T6</td>
<td>Tensile strength of 115 MPa was obtained by FSW.</td>
<td>[88]</td>
</tr>
<tr>
<td>39</td>
<td>Jedrasik et al. (2019)</td>
<td>Mg alloys &amp; Al</td>
<td>Heat generation in enormous strain welding technique was expected by small-strain “snapshot”.</td>
<td>[89]</td>
</tr>
<tr>
<td>40</td>
<td>Li et al. (2019)</td>
<td>AZ91 &amp; A383</td>
<td>Defect-free FSW weld between the A383 and AZ91 were achieved at 900 rpm and 40 mm/min.</td>
<td>[90]</td>
</tr>
</tbody>
</table>

Table 3 – Comparison of physical properties of iron, pure magnesium and aluminium at respective melting points [7,45].

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Iron(Fe)</th>
<th>Magnesium (Mg)</th>
<th>Aluminium (Al)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>BCC</td>
<td>HCP</td>
<td>FCC</td>
</tr>
<tr>
<td>Density (kg m⁻³)</td>
<td>7.015 x 10³</td>
<td>1.59 x 10³</td>
<td>2.385 x 10³</td>
</tr>
<tr>
<td>Melting point (⁰C)</td>
<td>1,536</td>
<td>650</td>
<td>660</td>
</tr>
<tr>
<td>Thermal conductivity (W m⁻¹ K⁻¹)</td>
<td>38</td>
<td>78</td>
<td>94.03</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (1/K)</td>
<td>1 x 10⁻⁵</td>
<td>2.5 x 10⁻⁵</td>
<td>24 x 10⁻⁶</td>
</tr>
<tr>
<td>Elastic modulus (N/m²)</td>
<td>2.1 x 10¹¹</td>
<td>4.47 x 10¹⁰</td>
<td>7.06 x 10⁻¹⁰</td>
</tr>
<tr>
<td>Specific heat (J kg⁻¹ K⁻¹)</td>
<td>795</td>
<td>1.36 x 10⁴</td>
<td>1.08 x 10⁴</td>
</tr>
<tr>
<td>Electrical resistivity (µΩ m)</td>
<td>1.386</td>
<td>0.274</td>
<td>0.2425</td>
</tr>
<tr>
<td>Surface tension (N m⁻¹)</td>
<td>1.872</td>
<td>0.559</td>
<td>0.914</td>
</tr>
<tr>
<td>Vapour pressure (Pa)</td>
<td>2.3</td>
<td>360</td>
<td>1 x 10⁶</td>
</tr>
</tbody>
</table>

* BCC, body centered cubic; HCP, hexagonal close packed; FCC, face centered cubic structure.

welding process is a non-equilibrium process [95]. Although equilibrium phase diagram is frequently used only for guidelines to predict the phase stability and probable chemical reactions occurs throughout FSW. The solvus line (not shown) conforms that the expected Al-Mg solubility at room temperature will be very less. It can be figured out that the binary phase diagram comprises two eutectic lines one at 450 °C and other one at 437 °C, which is much lower than the melting point temperature of pure aluminium and pure magnesium. The phase diagram contains three stable IMC phases, such as cubic β-phase, Al₃Mg [96], Al₁₃Mg₁₇, cubic γ-phase and rhombohedral R-phase or ε-phase [97]. Klag et al. [53] were observed that the magnesium alloys having about 8% aluminium content leads to a high strength β-phase at the grain boundaries and ductile α-phase with only a low content of aluminium. The microstructure of AA5454 H22 consists of an intermetallic precipitate of type Al₆ (Si, Fe, Mn) embedded in an aluminium solid-solution α-phase [53,98,99]. In Fig. 5(a-c), α-phase and β-phase of AA5454 and AZ91 is given. On account of the extremely confined solubility the blend of primary Al and Mg phase can form these two intermetallic compounds Al₁₂Mg₁₇ and Al₃Mg₂ in FSW of dissimilar Al-Mg. The IMCs formation mostly depends on the material composition and local temperature during FSW.

![Fig. 3 – Basic FSW tool-sample arrangement [51].](image-url)
is also related with several other dissimilar welding processes, namely; diffusion bonding [87,100,101], laser welding [45,102,103], friction stir spot welding (FSSW) [104,105], resistance spot welding (RSW) [106,107], tungsten inert gas welding (TIG) [108–110], metal inert gas welding (MIG) [111], ultrasonic spot welding [112,113], explosive welding [114] and cold metal transfer welding (CMT) [115,116]. Incomplete intermixing of weld nugget zone material is one of the most difficulties perceived in microstructure, which is occurred due to the lower peak temperature during Al-Mg FSW. It has been seen that continuous dynamic recrystallization (CDRX) during FSW is the key phenomenon for Al-Mg grain refinement [117,118]. The white bands having thickness of about 3 μm appeared at the Al-Mg weld interface, shown in Fig. 6(a,b), which confirms the presence of IMC layers [88]. Moreover, the XRD pattern displays in the Fig. 6(c), the Al12Mg17 phase formed at the joint due to the formation of Al-Mg solid solutions. The hard and brittle IMCs at joint interface of Al-Mg promotes micro crack and stress concentration by applying the higher load, consequently the joint fracture appears, shown in Fig. 7(a,b) [87,88]. While, in other fabrication process like transient liquid phase (TLP) bonding, the IMCs formation took place in a short time to complete the process [87,119,88]. Kreimeyer and Sepold have recommended that less than 10 μm of IMC thickness can be considered as better joint [120], while Qiu et al. [121] reported that IMCs thickness of 1.5 μm showed maximum joint efficiency during FSW of Al-steel. The thickness of the intermetallic layers are not constant and ranges between 0.5 and 1 μm, shown in Fig. 6(a,b) [64,88]. The characteristic of IMCs in Al–Mg weld comprises constant overlapping of brittle Al12Mg17 and Al13Mg2 layers [59,61,62,67,75,82,87,88,122]. Even though, it was observed that Al12Mg17 phase reveals better

3.2. IMCs formation and its effect

The most challenging task is to limit the hard and brittle IMCs layer formations at joint interface which degrade the ductility and strength of Al-Mg joints. This phenomenon regardless to the chemical composition of sample. Hence, the phase stability and weld morphology are much challenging to anticipate accurately as the peak temperature during FSW is rarely identified.

ductility at higher temperatures [123]. It was also observed during post welding that these IMCs phase shown insignificant plastic strains at ambient temperature.

During FSW of Al–Mg, the key factors provided in the available research literatures to describe the IMCs developments are based on either eutectic reaction or diffusion mechanisms. Lv et al. [124] described the formation of $\text{Al}_2\text{Mg}_{17}$ and $\text{Al}_3\text{Mg}_2$ in aluminium-magnesium binary phase system is due to the eutectics, Mg + $\text{Al}_2\text{Mg}_{17}$ (57% Mg) and Al + $\text{Al}_3\text{Mg}_2$ (37% Mg) at 437 °C and 450 °C respectively. Yamamoto et al. [67] reported that the FSW technique commonly works below the eutectic temperatures and hence the development of these IMCs takes place by diffusion mechanism among aluminium-magnesium atoms. Therefore, the IMC thickness is dependent of time and can be expressed as in equation (1) and (2) [125,126]:

\[
t^2 = \alpha \cdot t (1)
\]

\[
\alpha = \alpha_0 \cdot \exp \left(-\frac{Q}{RT}\right) (2)
\]

Where “t” is IMC layer thickness (m), “$t$” is time (s), “$\alpha$” is coefficient of diffusion ($m^2 s^{-1}$), “$\alpha_0$” is proportionality constant.

---

Fig. 6 – Microstructures of Al-Mg joint: (a, b) partial enlarged picture of uneven IMCs thickness at interfaces, (c) IMCs formation perceived through XRD analysis at joint [88].

---

Fig. 7 – Weld fracture locations obtained through (a) conventional FSW and (b) ultrasonic assisted FSW [88].
(m² s⁻¹). “Q” is stimulation energy (J mol⁻¹). “T” is temperature (kelvin, K) and “R” is real gas constant (8.314 J mol⁻¹ K⁻¹). Yamamoto et al. [67] have reported that the IMC Al₁₂Mg₁₇ phase growth rate is slightly quicker as compared to IMC phase Al₁₂Mg₁₇.

Conversely, the majority of researchers have reported that the key factor in IMC formation between Al-Mg is eutectic reaction [3,35,57,61,63,66,69,83]. In another research, Lv et al. [124] observed that the some parts of Al-Mg joint line are complex and circuitous IMCs distribution. Based on various IMCs location around the joint line can be differentiated generally into three types: type 1: coherent IMCs layer along the joint interface line, type 2: IMC fragments accumulated into magnesium matrix and type 3: IMC fragments accumulated into aluminium matrix and IMCs bi-layer (layer 1 and layer 2), which are shown in Fig. 8 [6,124]. The available literature suggests that constitutional melting or liquation promote the growth of IMCs. Since the eutectic lines lies below 200 °C of the pure aluminium and magnesium melting point even though adequate heat is generated to form local melting, i.e. eutectic reaction, which forms a thin liquid films and propagates along the grain boundaries same as occurs in case of transient liquid phase (TLP) bonding [119,126]. It is confirmed from the local chemical composition upon cooling, IMCs Al₁₂Mg₁₇ and Al₁₂Mg₁₇ are formed during Al-Mg welding through FSW process [66,69].

3.3. Phenomenon of material interlocking

Material interlocking phenomenon in dissimilar FSW material joining is a bond formation mechanism that depends on complex material flow behaviour around the joint interface. This phenomenon has been described to be one of the best methodology in improving the weld strength especially in dissimilar material joining through FSW, such as Al-Mg [74], Al-steel [127,128], Al-Cu [129] and Mg-steel [128]. It can be seen from Fig. 9(a–c) that both aluminium and magnesium are intermixed in solid form in stir zone and mechanical interlocking take place [6]. Firouzdar and Kou [3] also revealed that such mechanical interlocking phenomenon during FSW enhances the weld strength. Since low peak temperature is preferred in order to retard the IMCs growth rate. Nevertheless, it is also mentioned that IMCs formation at joint interfaces can also improve the bonding strength through proper stress distribution and material intermixing into nugget zone (NZ). Tool designs and positioning of workpiece are key aspects to

Fig. 8 – Types of the IMCs along Al-Mg joint interface (a, b) type 1: coherent IMC layers, type 2: IMC fragments accumulated into Mg side and type 3: IMC fragments accumulated into Al side, (c, d) IMCs bi-layer: layer 1 (Al₃Mg₂) + layer 2 (Al₁₂Mg₁₇) of thickness "3.5 μm [6,124].
Fig. 9 – Microstructure of Al-Mg FSW joint performed at 50 mm/min and 700 rpm (a–c) mechanical interlocking of Al-Mg [6].

enhance the appropriate mechanical interlocking [3,40,67,76]. But it was seen that the interlocking obtained in FSW do not attain periodic structures like those obtained during explosive welding [14].

3.4. Al-Mg joint interface

The development of chemical reaction based mechanical bonds in FSW joint interface varies considerably with workpiece material, tool configuration and offset, and other process parameters. From the above discussions it is concluded that a sound weld quality must comprises of thin and interlayered IMCs with highly intricate mechanical interlocking phenomenon. The joints having thin IMCs layer reduces the defects, whereas a complex mechanical bonding leads to a superior flow stress circulation [74]. A typical microstructure of Al-Mg diffusion region is shown in Fig. 10. The result indicates that there are two transitional phases that is β and γ, collectively known as terminal solid solution phases (i.e. IMC) in the diffusion region [125].

The attempt has been made to compare these various types of weld interface (i.e. type-1, type-2 and type-3 as already discussed in Section 3.2) to process parameters and weld quality perceived in the existing literature. With respect to microstructure of nugget zone (NZ) complexity, it will be tough enough to determine the overall strength in presence of intercalated layers and mechanical interlocking. On the
other hand, Venkateswaran and Reynolds [74] have projected few relationships i.e.: the weld strength can be a function of \((h/t)\) ratio i.e. interpenetrating feature (IPF) thickness \((h)\) and workpiece thickness \((t)\). And also dependent on the \((l/t)\) ratio i.e. total weld interface length \((l)\) and workpiece thickness \((t)\), are shown in Fig. 11(a). The length \(l/t\) was calculated as the total IPF length (white dashed lines in Fig. 11(a), whereas, “\(h\)” was calculated along the thickness of workpiece. As we can see clearly in Fig. 11(b, c) that any increment in \((l/t)\) and \((h/t)\) ratio, the weld tensile strength also increases. The basic reason behind this is due to: (a) the mechanical micro-interlocking which promotes micro-void coalescence (MVC) on tensile fracture surfaces, and (b) an increase in the brittle fracture zone essential to cause separation of the two halves of the tensile bar [74].

4. Influence of heat generation during Al–Mg FSW

In FSW, heat generation mostly occurs with three major aspects namely due to: (i) plastic deformation \(E_d\), (ii) viscous dissipation \(E_v\), and (iii) friction heat generation \(E_f\) at interface of tool and plate. In dissimilar material FSW like aluminium-magnesium alloys, these aspects are governed with another three factors such as; liquation susceptibility, variation in frictional coefficient and material deformability [81].

Zettler et al. [60] reported that the frictional coefficient of an Mg-tool boundary is lower as compared to Al-tool boundary. It was suggested that the contributions of \(E_d\) and \(E_f\) will be higher if greater surface contact between tool and Al will occur, such as provision to give tool offset towards the aluminium side. While, Yang et al. [130] measured the liquation susceptibility and found that the value is higher for AZ31 alloy as compared to 6061 alloy. The thin liquid films at tool/workpiece interface i.e. eutectic reaction \((\text{Mg} + \text{Al}_1\text{Mg}_17 \rightarrow \text{L})\) cause tool slippage and decreasing the resistance to tool rotation. Moreover, Fu et al. [81] observed that the constitutional liquation effect is predominant in dissimilar Al-Mg joining, causing low heat generation as compare to Al or Mg similar FSW.

The crystal structure explains the deformability of materials. Aluminium has face-centred cubic (FCC) crystal structure with twelve slip systems; however magnesium has hexagonal close-packed (HCP) crystal structure with having three slip systems only. Therefore, Al permits better deformability compare to Mg which promotes more heat input through \(E_d\) and \(E_f\) [66,81]. In concerns of heat input, Zhang et al. [131], and Song and Kovacevic [132] also calculated the heat input as mentioned in equation 3:

\[
\text{Heat Input} (HI) = \frac{Q_{\text{total}}}{v} = \frac{Q_{\text{shoulder}}}{0.83v} = \frac{2\pi \mu F_n R_s \omega}{0.83v} \text{(KJ/mm)} \tag{3}
\]

Where “\(HI\)” is heat input, “\(v\)” is welding speed (mm/min), “\(Q_{\text{total}}\)” represents the overall heat generation, “\(Q_{\text{shoulder}}\)” is heat generated by tool shoulder, \(\mu\) is frictional coefficient (generally taken as 0.3), “\(\omega\)” is rotating speed (rpm), “\(F_n\)” represents axial downward force (kN), and “\(R_s\)” is the tool shoulder radius (m) [131,132].

The heat input is increased by increasing the rotatory speed (referred equation 3), and the reaction between Mg and Al could occur with temperature. In Fig. 12(a, b), it is mentioned that the reason behind IMCs formation is heat generation and maximum temperature distribution followed by time. Mohammadi et al. [2] pointed out the principal reactions based
on aluminium-magnesium (Al-Mg) and magnesium-silicon (Mg-Si) phase diagrams are listed as follows:

\[
\begin{align*}
L &\rightarrow Mg + Al_2Mg_17 (473 °C) \\
L &\rightarrow Mg + Mg_2Si (595 °C) \\
L &\rightarrow Al + Al_2Mg_2 (450 °C)
\end{align*}
\]

The IMCs formation \((Al_2Mg_{17}, Al_3Mg_2, \text{ and } Mg_2Si)\) creates stable phases in stir zone. It is advisable to use optimum set of FSW parameters such as rotational and linear speed \([1,2]\). If the values of these parameters will be higher then: sufficient intermixing will take place, and lesser values will lead to voids formation but uniform distribution of IMCs. However, lower welding speed leads to high heat generation which stimulates the excessive IMCs formation of several kinds in the stir zone.

Micalef et al. \([133]\) reported that the heat input per unit length in correlation of the tool rotating speed \((\omega)\), the linear speed \((v)\) and tool shoulder diameter \((D)\). The developed dimensionless parameter is referred as the transverse heat input ratio (THIR) designated as \(\Phi\):

\[
\Phi = \frac{D \cdot \omega}{2v} \quad (4)
\]

The transverse heat input ratio (THIR) is one of the critical factors for determining the shape and size of stir zone (SZ). A higher THIR ratio (i.e. lower welding speed as compare to the rotating speed) leads to better uniform heating zone along the workpiece thickness (referred equation 4). But on the other hand, lower THIR ratio (higher welding speed as compare to the rotating speed) leads to high temperature gradients throughout the workpiece thickness \([133]\). In concern of heat input and heat dissipation, Ahmed et al. \([134]\) proposed to use the suitable fixtures (backing and cover plate) having heat resistant properties to reduce heat loss by conduction mode of heat transfer. Authors advised to use insulated fixtures made up of asbestos and marble. The key parts of the advanced fixture are (a) backing plate (b) clamp support (c) top clamp (d) cover plate (e) front clamp and (f) lateral clamps \([133,134]\).

5. **Parametric effect on dissimilar FSW**

There are several FSW process parameters which are known to be essential in providing quality and defect free joints, while few others have revealed the negligible effects on the dissimilar material FSW. As the process parameters will govern the weld properties (especially material flow and heat input). Therefore, it would be essential to give attention to those parameters having the utmost effect on these features \([5,75]\). The various FSW process parameters are discussed in subsequent section.

5.1. **Rotational and welding speed**

The tool linear speed, \(v\) (mm/s) and rotating speed, \(\omega\) (rpm) are possibly the most significant FSW process parameters, since both parameters have the substantial influence on the material flow and heat input. Generally, the heat input is directly proportional to the rotational speed and inversely proportional to the traverse speed, both factors are interrelated as (Eq. 5).

\[
\text{Heat Input} \propto \frac{\omega}{v} \quad (5)
\]

Therefore, both process parameters are imperative to produce a quality weld and higher ultimate tensile strength (UTS) hence these parameters need to be addressed properly \([135]\). By increasing rotational speed, the strained area becomes wider, and position of maximum strain region moves towards advancing side (AS) from its initial retreating side (RS) of the weld. This indicates that the fracture position of the weld is also get affected by tool rotational speed \([13,136]\).

On account of compounding effect of both process parameters, various researchers have reported the term revolutionary pitch \((v/\omega)\) which affects the weld quality \([137-139]\). A higher revolutionary pitch value manifests a fast welding (i.e. cold welding), whereas a lower pitch value manifests a slow welding (i.e. hot welding) \([140]\). Higher pitch ratios account inadequate material flow and low peak temperature, whereas a too low value will cause adverse material flow and higher liquation which promotes IMC growth, both conditions detrimental to the weld quality \([83,130,141]\). Lower rotational speed
leads to low temperature generation in the nugget zone (NZ) and the volume fraction of coarse second phase (strengthening) particles increased, as shown in Fig. 13(a,b). While at higher rotational speed, second phase particles undergo more fragmentation shown in Fig. 13(c,d) and leads to particles separation in other section of the TMAZ [13].

In reference to Al–Mg dissimilar FSW, the research studies suggested that the revolutionary pitch ranging from 0.02 to 0.38 mm/rev is favourable (referred Table 2) [3,6,23,24,35,57–90]. The joint efficiency (η) is a parameter which refers the joint quality and defined as the ratio of weld ultimate tensile strength (UTS) to the base metal UTS having lowest value in case of dissimilar joining. Fig. 14 represents the various set of parameters with associated defects [43]. The rotating speed ranging from 600 rpm to 800 rpm and the welding speed ranging from 30 mm/min to 60 mm/min resulting into quality and defects free weld. The values outside of the given frame i.e. beyond 800 rpm and below 600 rpm, shows the defects formation like cavity having area less than 0.02 mm² and tunnel defects having area more than 0.05 mm². In exceptional cases, weldments failed through surface crack and fracture along the joint line having the defect area greater than 1 mm² [43].

The higher weld strength was achieved with proper set of rotational speed between 600–800 rpm and welding speed between 30 and 60 mm/min. While at higher rotational and traverse speed were resulted into the lower weld quality [43]. The relation between UTS vs. welding speed graph in Fig. 16(a, b) shows that the UTS of the joints rose with increased welding speed at constant rotational speed. The tensile results can be demonstrated with the precipitates evolution in the heat affected zone (HAZ). The increasing density and slight coarsening of β' led to a relatively higher strength [43,142]. The percentage elongation versus welding speed correlation also mentioned in the Fig. 16(b). Since the traverse speed increases, the percentage elongation also increases. The main reason works behind this is the amount of heat input and IMCs formation. Higher welding speed results into lower heat input (refer

Fig. 13 – Influence of rotating speed on microstructure of FSW zone at: (a) 800 rpm (b) 1000 rpm (c) 1200 rpm (d) 1400 rpm [13].

![Microstructure of FSW zone](image)

Fig. 14 – Various defects at different welding and rotational speeds keeping Mg-alloy on advancing side [43].

![Graph of UTS vs. welding speed](image)
Eq. 4) and consequences into lesser IMCs formation which makes stir zone (SZ) less brittle [13,135,142].

Buffa et al. [143] reported that the effect of tool rotating speed (at 500, 700 and 1000 rpm) on temperature and strain distribution shown in the Fig. 15(a, b). Firstly, a uniform temperature distribution along with non-uniform strain distribution can be observed by increasing the rotatory speed. Any increase in the specific thermal contributions (STC) which is deliberated at the weld joint, resulting in the wider stir zone area obtained (refer Fig. 15b), with potential effects on the material intermixing. This is because of the increase in tool rotational speed that allows a single material particle to

---

intermix with the tool having a wider trajectory and hence accumulating additional strain [142,143].

On the other hand, any increment in the expected temperature by increasing of STC value is such that, around the weld nugget (WN), substantial temperature distributions are also found in the weld TMAZ and HAZ area which leads to detrimental effects for the weld strength due to the grain growth phenomena [43,143].

5.2. Tool design and geometry

Tool design and configuration plays an as equal important role as other parameters in formation of better joint. The most commonly used material for FSW tool for Al-Mg is H13 steel, addressed in Table 1, while few other tool material reported are AISI tool steel [78], high strength steel [59], SKD51 steel [70], SKD61 steel [61,62,67] and H13 steel shoulder coupled with MP159 cobalt base super-alloy probe [84,74]. Ugendor et al. [144] reported that the materials hardness used for FSW tools namely; mild steel, stainless steel, armour steel, high carbon steel and high-speed steel is 30, 40, 58, 66 and 73 HRC respectively. As for tool geometry concern, the threaded and cylindrical configurations both are equally utilised. Whereas, it is noteworthy that various researchers were used the probe having threads/flutes [3,60,74,76,81,83,87,145,146]. Threads and flutes not only play an important role to improve the material flow behaviour during FSW but also increases the heat input due to its large surface area [147]. The FSW tools are mostly categorized into three types: (i) fixed type, (ii) self-reacting or bobbin type and (iii) adjustable type tool.

Fixed-type FSW tool is recommended when the workpiece thickness is uniform. Whereas if pin length varies during welding then adjustable-type tool is suggested because it contains two distinct tool component i.e. pin and shoulder. The self-reacting type tool is assembled with three distinct bodies, such as the pin, top shoulder, and the bottom shoulder and it is also known as bobbin-type tool. The Fig. 17(a–c) displays the three distinct types FSW tool [147,148]. It is stated in numerous research that the FSW tool design and configuration has its own significant effects on the weld performance such as; micro hardness, mechanical strength and associated defects.

5.2.1. Tool shoulder and pin geometry

The selection of an optimal tool shoulder geometry and dimension is considered as the key factors during FSW to achieve a quality and defect-free fabrication. The tool shoulder shares two major effects: (i) vertical compressive force and (ii) thermal heat generation due to friction [5,150]. Moreover, various researches have chosen shoulder with concave geometry. Lin et al. have revealed that mechanical and microstructure properties of the joint considerably enhanced by using concave tool shoulder instead of flat. Material near the top surface is pushed toward the advancing side due to the shoulder effect [151–153]. Exceptional tool geometry combinations having threaded pin with 5-flats and 10° taper used by Zettler et al. [60] may have also proved an impressive joint efficiency up to 88%. It has been shown that tool shoulder dimension plays a critical role and contributes nearly 87% of total frictional heat accomplished during stirring process between the surface of workpiece and shoulder [1,50,150]. The various FSW tool shoulder and pin surface configurations are shown in Figs. 18 and 19.

The pin or probe configuration and its dimension also play a crucial role on weld quality. Its impact directly affects the stir zone size, material flow and microstructure behaviour during FSW. The tool probe performs shearing of the material in to and fro direction of the tool and plastic deformation takes place [47,154–158]. Various studies illustrated the slight variations regarding the probe length and suggested the difference of workpiece thickness and probe length (Δt), is usually small (Δt ≤ 0.5 mm) so that a suitable fabrication along the plate thickness must be projected. On the other hand, Pourahmad et al. [75], McLean et al. [57] and Yan et al. [59] have used a greater difference of Δt i.e. 4 mm, 1.4 mm and 1 mm respectively. The large difference Δt may cause in insufficient material intermixing at weld root and may encourage to weld premature failure.

The effect of pin length and workpiece thickness difference has noted by various researchers, McLean et al. [57] have described that the AZ31B-AA5083 joint was quite weak so that even small forces during polishing process were enough to initiate the crack in the weldment. However Pourahmad et al. [75] obtained the weld efficiency of 19% only. In contrast, Yan et al. [23] achieved a better joint efficiency of 67%; this was due to the better material flow using threaded pin. Another aspect in continuation of shoulder and pin dimension is SPR ratio (shoulder-pin diameter ratio). It is described as the ratio of shoulder to pin diameter. The SPR value for dissimilar material joining is related to thickness of the sample. It is somewhat lower for similar material FSW joining and higher for dissimilar joining [47,75,154].

Srinivasa et al. [159] reported that the consequences of tool rotating speed, feed rate and pin configurations. Authors concluded that the FSW pin configuration, feed rate and rotary speed are having direct impact on weld tensile strength. The correlation among them has shown in Fig. 20(a–c). The optimum value for percentage elongation, ultimate tensile strength (UTS) and joint efficiency are seen at traverse speed of 80 mm/min at constant rotating speed of 1000 rpm. Even though the UTS of weld were lower than that of workpiece, the joint efficiency is satisfactory if we compare the joint efficiency with any fusion welding process. Lower shoulder diameter shows inadequate heat generation during FSW and exhibits tunnelling defects [154,159].

5.2.2. Tool positioning or offset

Tool positioning or offset appears, if the tool shifts intensely from the workpiece centre line towards the either plate (i.e. advancing side or retreating side). It may also define as the FSW tool axis line deviates from centre distance of sheet adjoining edges. Zero or no tool offset take place when pin is positioned exactly at the weld centre line [160,161]. The basic schematic tool offset is shown in Fig. 21. Usually, high strength alloys needs higher heat input to get plasticised during FSW and vice versa. Therefore, it is necessary to give proper offset during dissimlar material FSW. In case of dissimilar material fabrication heat distribution is not balanced because of different thermal conductivity of materials and thus by giving offset it would be balanced. If a suitable amount of tool offset is given to softer material (i.e. towards harder material) then the tool would be able to stir the both material effectively [162]. An optimum and appropriate tool offset come to be essential during dissimilar material joining. Preceding research shown that if welding is done with zero pin offset resulting into poor weld qualities comprising various defects [163]. Most of the studies, showing tunnel defects, and the main cause have been reported due to the less heat input. The microstructure and associated defects can be seen in Fig. 22(a–d) [162,164]. The most prominent and conventional method in tool offsetting is to shift the tool along the abutting edge of the two plates [16,17,60–64,79]. Yamamoto et al. [67] claimed that the zero pin offset is favourable, as pin offsetting to the Mg side or Al side will produce defects like surface flash and internal cavities. However, several other researchers’ revealed that giving tool offset is an important aspect during joining of Al–Mg through FSW [66,76,80,83]. The tool positioning by giving proper offset will decide the material intermixing in the weld from both sides [40]; but, it is quite challenging to evaluate the SZ and overlapped areas by either side of the material since various tool design and material properties would also be taken into consideration.

Baghdadi et al. [161] explained the tool offset effect on AZ31B and Al6061-T6 dissimilar FSW weld. Author found that for Al–Mg dissimilar joint zero (0) offset i.e. in the middle, the weld appearance was smooth and with less flash formation and flush out from the weld area during the fabrication process. Moreover, the amount of the flash formed in −1 mm tool position was more than +1 mm tool position [161]. In the same context, Watanabe et al. [165] studied the tool offset effect on mild steel to aluminium alloy joining. The maximum weld ultimate tensile strength (UTS) was attained at tool pin offset of 0.2 mm towards steel side. At a higher offset, steel particles were fragmented in aluminium matrix. These fragments were large enough in size to form voids resulting into decrease in weld tensile strength. In Fig. 24(a), it is clearly explained that the pin offset effect on tensile strength and microstructure of the weldments. Keeping pin offset too high and too low leads to a detrimental weld quality and degrades the mechanical properties. On the other hand, fragments of hard material dispersed into the soft material matrix leads to fracture during tensile test, shown in Fig. 24(b–c) [165]. The aluminium-magnesium binary phase diagram (referred Fig. 4) indicates that the eutectic temperatures are slightly lower i.e. 437 °C and 450 °C. Therefore, during FSW process for Al-Mg,
this temperature may be reached. The greater the peak temperatures the most likely the stir zone may stagnant above the eutectic line. Therefore, a substantial variation in the peak temperature may affect by varying the travel speed, workpiece position and rotational speed which is counted as a noteworthy effect on weld strength [3].

The tool offset effect on the morphology and structure of dissimilar FSW weld was also studied by Sahu et al. [166]. Authors were observed that the huge formation of IMCs rich structures which severely affects the tensile strength and surface behaviour of the weld. Providing tool pin offset influences the material flow behaviour and volume fraction of IMCs positively, which results in minimizing the defects and provides good quality joint during dissimilar FSW [167,168]. Provision of pin offset also supports optimum heat distribution in the weld zone. The optimum pin offset value mainly depends upon the sample composition, thickness and tool design [160,169,170]. Therefore, it is important to choose the optimum tool offset value for Al-Mg dissimilar material FSW.

5.3. Effect of tool tilt angle

The FSW tool tilt angle is defined as the relative position of tool to the plate surface. When the tool is vertical or perpendicular to the plate surface then this position is called as zero or no tilted [171]. The joint quality depends on tool tilt angle also [172–174]. A suitable tool tilt angle comprises three basic purpose as: (i) confirms the proper holding of forged material
Fig. 20 – Effects of FSW pin configurations and traverse speeds at constant rotating speed of 1000 rpm on: (a) % elongation of joints (b) ultimate tensile strength (MPa) and (c) joint efficiency [159].

below the tool shoulder [47], (ii) offers an identical material flow behaviour [47,173] and (iii) increases the temperature around FSW tool area in the advancing side of the workpiece [175]. The basic schematic diagram of tool tilt angle is shown in Fig. 25 [175]. The front portion is called leading side and back portion is called trailing side of the tool tilt.

Meshram and Reddy [176] deliberated that the tool tilt angle effect on material flow with an angle ranging 0° to 3°. Authors observed surface defects at 0°–0.5° and beyond 0.5° tilt angle surface defect were absent. However, weld made in the range of 2.5° and 3° shown internal kissing bond defects which prone to large voids at the subsequent increase in tool tilt angle up to 3° [176]. Moreover, Banik et al. [177] examined the weld quality of Al 6061-T6 through FSW. They observed that any increment in tool tilt angle increases the torque and forces at the tool/workpiece interface. Hamid and Roslee [178] also investigated the tool tilt angle effect on the microstructural and mechanical behaviour of dissimilar aluminium alloys. The weld microstructure varied considerably by changing the tool tilt angle, specifically in the weld nugget and heat affected zone. Moreover, Shah et al. [179] analysed the tool tilt angle effects on the mode of fracture during tensile test. It was perceived that the defects free joint having best mechanical and metallurgical properties obtained with 2° tilt angle. Authors

Fig. 21 – Three different tools offset position with respect to AZ31 Mg alloy: (a) tool offset of −1 mm (b) tool offset of 0 mm and (c) tool offset of +1 mm [161].
also used SEM for analysis to identify the surface fracture failure patterns through tensile specimens test. From Fig. 26(a), it is shown that the fracture surface with the presence of pits defining a ductile fracture mode. But on the other hand, a brittle fracture failure was found in all other weldments, shown in Fig. 26(b, c). It is clearly observed that an irregular surface associated with fibrous and tedious appearances which are clearly indication of a brittle fracture failure [179].

It was stated that a constricted weld obtained with greater tilt angle and avoids material scattering over top surface (i.e., flash effect). Hardness value also increases at weld zone with any increase in tilt angle due to rise in temperature which leads to huge IMCs formation [174]. Hence, it is fundamental to choose an appropriate tool tilt angle during FSW of Al – Mg dissimilar joining.

5.4. Base metal positioning

Positioning of workpiece is an important factor during dissimilar FSW of Al – Mg [169]. Generally, there are two known

Fig. 22 – Microstructure of (a) various FSW region and defects and (b–d) tunnelling and kissing bond defects present [162].

Fig. 23 – Average peak temperature in various weld regions with a given tool offset and welding speed, when: (a) Al on advancing side and (b) Mg on advancing side [3].
positions in FSW methods i.e. advancing side (AS) and retreating side (RS), shown in Fig. 3 [141]. If the direction of welding feed and the tangential direction of the rotating tool will be similar then this is known as the advancing side. Whereas, if both direction is in opposite with each other, known as the retreating side. It is stated that the material intermixing behaviour and IMCs formation are considerably subjected to workpiece positioning during dissimilar alloys FSW [3,48,160,180,181]. In general, if the harder workpiece (plate) is fixed at the RS, it offers resistance to move in AS and marks into irregular material flow. These irregular materials flows cause voids and tunnels defects and also try to extrude out the plasticized material from the weld nugget zone [160,169,182]. Positioning of workpiece during lap joint arrangement is also an issue of concern. During FSW of Al-Mg, it is suggested to keep the Mg plate at the top and Al plate at bottom to attain a proper mixing and better weld quality. The thermal conductivity of Mg is lower than Al, which creates better material flow and generates appropriate heat into nugget zone [3,143,160].

According to the Schneider–Nunes kinematic model [183], plasticised material (soften material) on the retreating side is just deposited behind the FSW tool from the front, like ‘straight through’ current. However the sample placed at advancing side experiencing various rotations before being deposited at a lesser height as compare to base height such as ‘maelstrom’ or ‘whirlpool’ current.

During similar material joining through FSW, it was observed that through various thermocouple and simulations which indicates more heat develops on the advancing side rather than retreating side [184–187]. Though stirring action experiences on both side (i.e. AS and RS), but direction of tangential velocity makes the heat difference on the AS and RS [66]. Furthermore, in similar material FSW i.e. aluminium and magnesium separately, Zettler et al. [60] and, Firouzdor...
and Kou [3] have confirmed that aluminium alloys of 6××× series reveals higher maximum temperatures as compared to magnesium counterparts. On the other hand, similar material FSSW i.e. aluminium and magnesium by Gerlich et al. [104] and Yang et al. [188] also have revealed a similar results.

According to these facts from various literatures, it can be quantified that dissimilar material positioning at either side i.e. AS or RS, can give significantly different mechanical and microstructural behaviours; two consequences can be projected in case of Al–Mg FSW: (i) probably higher heat generation can be predicted with aluminium on advancing side, and, (ii) possibly the higher heat generation can also be predicted with increase of contact area between FSW tool and aluminium plate i.e. tool offsetting on aluminium side. Contrary to this, as greater shearing/stirring action is expected on advancing side, employing the magnesium alloy which shows higher liquation tendency, lower deformability and lower coefficient of friction as compare to aluminium alloys on this side recommends a lower heat generation through plastic deformation (Ea), frictional heat (Ei) at workpiece/tool interface and viscous dissipation or material flow phenomenon (Eo) [3,40,66,81].

Among the initial progresses, Sato et al. [35], were successfully produced the butt joints FSW of aluminium alloy 1050 and magnesium alloy AZ31 grade by keeping Mg alloy on the AS and Al alloy on the RS, whereas by switching their positions headed to ineffective fabrication. Other succeeding reports have also proposed similar setup position [44,60,64,66,71,76,77,80]. In contrast, the widely available studies have recommended the aluminium on AS and magnesium on RS which produces better weld metallurgical properties [16,57–59,61–63,65,67,68,70,72,73,75,79,82,85]. This position is known for promoting higher process temperature and enables effective material plasticisation [73]. If one stick with particular Al alloys used, it seems that Al-alloys of 2××× and 5××× series are always give better result on advancing side, whereas Al-alloys of 1××× and 6××× series are somewhat position flexible ability, however several opt for employing it on retreating side. This is probably because of lower stress flow property of 1××× and 6××× Al-series as compare to 2××× and 5××× Al-series even at higher temperatures [35,57–60,63–66,189–191]. The material position and its effect on weld quality of 1×××, 2×××, 5××× and 6××× Al-series with AZ31B Mg alloy are represented in Table 4. None of the researchers reported the comprehensive data for magnesium alloys comparing the flow stress to aluminium alloys, but Sheng and Shrivpuri [192] have little information on the flow stress of magnesium AZ31B alloy. They were found strain rate of 2.0 s⁻¹ and the maximum flow stress of 220 MPa at 200 °C. However, the strain rates are not comparable therefore this set of data was estimation only. It can be predicted that the flow stress of magnesium alloy decreases to a minimum value by lowering the strain rate. It should also be distinguished that at higher peak temperatures the slip activation system in magnesium alloys will be more, and previous research has revealed that at higher rotational speeds, the torque produced

Fig. 26 – SEM micrograph of fracture plane of FS welds at (a) 2◦ tilt angle (b) 4◦ tilt angle and (c) 6◦ tilt angle [179].

Table 4 – Effect of material positioning (Advancing side) during FSW of various Al alloys to AZ31B Mg alloy.

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Al alloys</th>
<th>Material positioning on Advancing side</th>
<th>Welding parameters</th>
<th>Remarks/conclusion</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al-5083</td>
<td>Al</td>
<td>RS:300–400 rpm;</td>
<td>Better joint obtained. Very thin IMC layer obtained at the interface results in welds with very less ductility.</td>
<td>[57]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:60–100 mm/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Al-1050</td>
<td>unspecified</td>
<td>RS:1500–3000 rpm;</td>
<td>Joint efficiency obtained around 77%. Fracture occurs near the IMCs formed in the weld interface.</td>
<td>[189]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:200–800 mm/min; Tool tilt angle:3;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Al-1050</td>
<td>Mg</td>
<td>unspecified</td>
<td>Al12Mg2 and Al12Mg6 IMCs obtained. Diffusion occurred at the weld interface.</td>
<td>[190]</td>
</tr>
<tr>
<td>4</td>
<td>Al-6061</td>
<td>Al, Mg</td>
<td>RS:800 rpm;</td>
<td>Fine transitioning of 6061-T6 into the weld zone was observed.</td>
<td>[58]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:90 mm/min; Tool tilt angle:1;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Al-1050</td>
<td>Al (failed), Mg (successful)</td>
<td>RS:2450 rpm;</td>
<td>The IMC Al12Mg6, was possibly formed due to constitutional liquation during FSW and it results into high hardness at interface.</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:90 mm/min;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Al-1060</td>
<td>Al</td>
<td>RS:200–1000 rpm;</td>
<td>The FS weld shows complex vortex flow intercalation lamellae. Joint efficiency is 67%.</td>
<td>[59]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:19–75 mm/min; Tool tilt angle of 3;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Al-6040</td>
<td>Al, Mg (strong weld)</td>
<td>RS:1400 rpm;</td>
<td>Joint efficiency was 80%. Brittle IMCs Al12Mg2 and Al12Mg6 were formed but only in localised regions of stir zone.</td>
<td>[60]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:200–225 mm/min; Tool tilt angle of 2.5;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Al-5052</td>
<td>Al</td>
<td>RS:800–1600 rpm;</td>
<td>Joint efficiency was 67%. The maximum tensile strength was about 132 MPa.</td>
<td>[63]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:300 mm/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Al-6040</td>
<td>Mg</td>
<td>RS:1400 rpm;</td>
<td>Two IMCs (fine-grained Al12Mg2 and nano-sized-grained Al12Mg6) were observed.</td>
<td>[64]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:225 mm/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Al-2024</td>
<td>Al</td>
<td>RS:500 rpm;</td>
<td>The corrosion attack was detected in the fine sections of AZ31 alloy nearby Al-2024 areas.</td>
<td>[65]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:45 mm/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Al-6063</td>
<td>Al</td>
<td>RS:900–2700 rpm;</td>
<td>Weld joint failure occur through the IMC layer present at the interface.</td>
<td>[191]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:102–384 mm/min; Tool tilt angle of 3;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Al-6061</td>
<td>Al, Mg (strong weld)</td>
<td>RS:1400 rpm;</td>
<td>Material position that favours a lower heat input which increases the joint strength.</td>
<td>[66]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WS:38 mm/min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RS, Rotational speed (rpm); WS, Welding speed (mm/min).

by the rotating tool in magnesium AM50 alloy is much lower as compare to aluminium 6061 alloy in the similar conditions [192]. It is concluded that the lower flow stress value of 1××× and 6××× aluminium alloys series having better material amalgamation and intermixing irrespective of workpiece positioning. Conversely, Al alloys of 2××× and 5××× series which shows better flow stress as compare to magnesium counterpart that seems to be placed on advancing side to improve plastic deformation and material intermixing. Therefore, it is essential and needful area of research to identify the best possible position for Al-Mg dissimilar FSW.

5.5. Base metal thickness

Workpiece thickness is one of the key deciding factors during tool design configuration selection and other FSW process parameters. Any variation in workpiece thickness affects the stirring action, weld nugget thickness and rate of heating and cooling. Fabrication of a comparatively thicker workpiece by using a short tool pin produces an inadequate bonding up to the weld root [160,161]. Aluminium alloys have been welded from thickness of 0.5 mm–65 mm using FSW without having any defects like voids and porosity [193]. Various researchers have been successfully joined the aluminium and magnesium up to 8 mm by using FSW technology [13,52,142,193]. Further studies are required for joining of Al-Mg alloys particular to thickness of more than 8 mm and less than 1 mm (micro-FSW).

6. Relating the process parameters to the response variables

It can be attempted to examine each and every parameters individually to get into correlations with joint consequence. However, the fact is that all process parameters are having mutual dependency with one another to a definite level. Consequently, these process parameters influence the many response variables, such as; heat generation, power, torque, and rate of cooling, which successively affects the workpiece response. Various important friction stir welded response or dependent variables are considered below.

6.1. Power and torque

Firouzdor and Kou [3] have revealed that joining of similar aluminium 6061 alloy through FSW produced considerably higher power and torque as compared to similar magnesium AZ31 alloy with similar parameters. This comparative study can be seen in Fig. 27. The study showed two remarkable phenomena: (i) the torque amplitude oscillation appears to be
Fig. 27 – Response variable of dissimilar metal (6061-AZ31) FSW variation at 1400 rpm with: (a) time-torque (b) time-power [3].

higher in FSW of dissimilar material than in FSW of similar material and; (ii) the torque initially increases very slowly and steadily reaches to a lower value in FSW of dissimilar material than in FSW of similar material [3]. During dissimilar FSW of Al6061-AZ31, power and torque rises by increasing traverse or welding speed. These two values were also considerably higher and increase in heat input, when Al alloy 6061 is employed on advancing side. However, lower heat generation was observed by any decrease in power and torque during dissimilar FSW of Al–Mg comparing to similar FSW on either side of the material. This advocates liquidation phenomenon after aluminium-magnesium eutectic reaction, as stated previously, which leads to tool slippage and describes the greater torque oscillation amplitude because of ‘slip-stick’ phenomenon during FSW of Al–Mg [69,44].

Venkateswaran and Reynolds deliberated the parametric effect on power and torque stated on magnesium AZ31B-H24 alloy and aluminium 6063-T5 alloy through FSW [74]. Power calculation was obtained by the product of rotational speed and its spindle torque. It was seen that the torque was decreased as tool rotating speed were increased from 900 rpm to 2700 rpm, which classified a better material flow behaviour and hence it is concluded that there is a direct dependency of tool rotation on response variable. This decline in torque value is much more than the value compensated by rising in welding power with rotating speed, subsequently greater heat generation. Hence, higher grain growth rate appears at weld nugget zone (WNZ).

6.2. Effect of peak temperature on FSW weld

The measurements of peak temperature can be done by means of thermocouples placed inside the tool pin or within the sample, were reported in various research literatures. Azizieh et al. [83] used a thermocouple of K-type placed at bottom side of the sample for temperature measurements. The highest tensile strength was achieved at peak temperature ranging 430 °C–460 °C i.e. eutectic temperature. It was also revealed that by increasing peak temperatures the hardness value and the amount of IMCs formation were increased in weld nugget zone. Higher rotating speed and the average peak temperature leads to form an oxide on the top surface and leads to liquation and IMCs formation whereas, at higher rotational with high linear speed obtained a greater weld strength. But in case of higher rotating and lower welding speed, better corrosion resistance property was perceived [49].

Dialami et al. [194] demonstrated that there is an uneven frictional interaction between the workpiece and tool. The sample material is being stirred in presence of frictional contacts. The peak temperature of the FSW tool is reached in the place where maximum material stirred has been taken place from retreating side to the advancing side of the workpiece position [194].

The thermocouples were embedded at distance of 3 mm from either side of the faying surface and 1.35 mm down to the top plane of the sheet, Firouzdar and Kou [3] confirmed that higher peak temperature value was observed on the aluminium side irrespective of workpiece positioning. Later on, it was also validated by Fu et al. [81]. Zettler et al. [60] conducted the temperature measurements set up at mid of plate thickness i.e. 10 mm from the joint centre also concluded peak temperature was higher on aluminium side predominantly when it was located on advancing side. In another report, Firouzdar and Kou [3,69] also described that for getting higher peak temperature, locating the aluminium plate on advancing side (AS) and also tool offsetting to aluminium side. Whereas, keeping the magnesium alloy on advancing side and tool offsetting to aluminium side was shown lower peak temperature, refered in Fig. 23. Subsequently by keeping the same parameters, tensile test reveals that the heat input generation increases and weld strength decreases. Fu et al. [81] also stated that setting of higher tool offset to aluminium side leads to a higher peak temperature as well as higher heat generation. Azizieh et al. [83] also reported the peak temperature effect on IMCs, stir zone grain size, and hardness of the joint. From the Fig. 28(a), it can be seen that the formation the IMCs are mainly concerning with the peak temperature. The temperatures, at which there is almost no formation of IMCs (Al$_3$Mg$_2$ and Al$_{12}$Mg$_7$), are 350 °C and 240 °C.

It was reported that in these temperatures the FSW tool was stopped in the samples and no weld was made. Therefore, it is impossible to eliminate the IMCs layer fully by regulating the welding parameters. On the other hand, the average peak temperature effect on the stir zone grain size on the magnesium side is explained in Fig. 28(b). It was clear that an increase in peak temperature resulting into grain growth having higher grain size as compare to lower temperature result. Conversely, above 500 °C (at 750 rpm) the grain size was uniform and constant [83]. Higher liqution is the main cause for getting uniform grain size due to decrease in frictional heating throughout the FSW [6]. The hardness value increases gradually by increasing the peak temperature up to 460 °C and after that a rapid increment were observed. The maximum hardness value obtained somewhere in the middle of stir zone which was almost double of the base material [6,39,80,83].

### 6.3. Cooling effect on FSW weld

The cooling process is a best technique for metals and various alloys that are sensitive at higher temperature during fabrication. It is an improved method for creating ultra-fine grained joint materials. Mofid et al. [73] obtained a sound quality joint with reduction in peak temperature value by using external water cooling system for AZ31C-O Mg and 5083 Al.
FSW, whereas Zhao et al. [82] have stated that the similar result when an underwater FSW (UFSW) technique was executed on FSW of Mg-AZ31 and Al-6013 alloy [73,82,85]. However, in a latest research studies by Miyamori et al. [195] have also reported the use of UFSW on carbon steel obtained greater torque and compressive force in z-axis comparing to traditional FSW, since water cooling limits the temperatures and most likely increases the flow stress necessary for the plastic deformation of material [195].

The rate of cooling during underwater FSW (UFSW) is faster than in air, since specific heat of water is almost four times the air [82]. A higher rate of cooling indicates the grain growth in the heat affected and weld nugget zone can be quite limited. It would also be pointed that rate of cooling may differ from surface to surface i.e. varying with weld thickness. Zettler et al. [60] stated and observed that an increase in hardness value on the bottom portion of Al6040-AZ31 alloy fabricated through FSW. The bottom surface recommends a rapid cooling as compared to other sample surfaces; probably due to the direct surface to surface interaction with the backing plate which acts as a heat sink [60].

Zhao et al. [85] also reported the cooling effect on hardness and tensile strength of the Al-Mg dissimilar FSW. Authors found that the average base materials hardness of Mg-AZ31 alloy and Al-6013 alloy are 65 HV and 125 HV respectively. In Fig. 29(a–c), it is given that the considerable variation observed with both i.e. water and air cooling effect on tensile strength and hardness value. The welds obtained in air conditions have 131 MPa of ultimate tensile strength (UTS). While, UTS of 152 MPa was achieved through UFSW, which was roughly 64% of magnesium AZ31 alloy. The percentage elongation of weld via UFSW was 1.3%, which was higher than the normal FSW, shown in Fig. 29(c). But with IMCs formation, the elongations were quite lower than workpiece materials [85]. The basic reason to get the better weld joint by submerged FSW is to form smaller temperature gradient around weld. Water is more capable of cooling down the joint as compare to air and produces a better weld quality.

In addition to this, another possible technique to limit the peak temperature is by using feedback control system like reported by Ross and Sorensen [196]. An in-built thermostat assures that the favourable temperature is asserted by regulating the tool rotating speed in actual time. Not only it maintains the temperature but also reduces the weld properties variation all over the joint interface, prolongs tool life and increases repeatability. Though it is very beneficial but feedback control arrangement is very complex and expensive. It is confirmed from the previous literatures that very limited studies has been done so far relating to any temperature control system regards to Al-Mg FSW. Therefore, it becomes very interesting and much needed area of research in future on dissimilar FSW of Al-Mg.

6.4. Material flow behaviour

The FSW process comprises of a very complicated phenomenon with regard to material flow and plastic deformation. The FSW working parameters play an important character in temperature distribution and material flow behaviour phenomenon. The material flow patterns is greatly

![Fig. 29 – Cooling effect on weld under various conditions: (a) horizontal hardness profiles underwater and in air conditions (b) hardness across the thickness underwater and in ambient air and, (c) percentage elongation and tensile strength of weld and base materials fabricated underwater and in air conditions [85].]
Fig. 30 – Material flow behaviour with: (a) simple geometry (b) complex geometry (c) a typical material flow behaviour representation [48,87,149].

rely on tool pin geometry, flow stress, working temperature and axial compressive force, which is shown in Fig. 30 [51,48,87,149]. During fabrication process, FSW tool offers two primary functions; (i) material flow and (ii) localized heating. Complicated material flow behaviour severely changes the weld nugget zone microhardness [160]. The material flow pattern in similar and dissimilar FSW is quite different since onion ring structure is commonly found in stir zone of similar material FSW [197], while during dissimilar FSW, intercalated vortex type structure is found all over stir zone [198]. Complex forging or stirring action is occurred at bottom region and it produces intercalated swirl like structure whereas a composite like pattern produces in upper portion of the weld nugget zone [199]. Therefore, provision of pin offset is compulsory and it gives positive effects on the material flow behaviour and IMCs formations’, resulting in minimize the defect and produces a better joint during dissimilar material FSW.

Feistauer et al. [200] discussed the multi-pass welding effect on material flow pattern at constant tool rotational direction. Thus, it increases the material intermixing and considerably reduces the kissing bond defects, particularly at retreating side of the T-Joint.

Pourahmad and Abbasi [75] recognized that the three different regions at weld interface along thickness of the workpiece. The first region is pointed to the upper portion of the weld, where material is plastically deformed and its flow behaviour is strengthened with effect of the tool shoulder. Weld material islands and mechanical interlocking are perceived only in the upper part of the joint. On the other hand, the second region is pointed in the middle section of the weld, the weld interface become smoother and the extrusion of Al into Mg is less. The third region is near the probe bottom in which the extrusion of Al into Mg is the least. The unlike material flow and different penetration forces are the result of these various regions.

Fig. 30(a, b) indicates the streamlines flow across threaded and unthreaded and pins during FSW process. It can be seen from the Fig. 31(b) that the weld material is simply pushed into the stir zone with threaded pin configuration [201]. It is
7. Microstructural and mechanical behaviour of dissimilar Al-Mg FSW

Microstructural area of friction stir welded material are classified into four regions: two regions are outside the shoulder i.e. heat affected zone (HAZ) and parent material microstructure, and two regions are beneath the tool shoulder area i.e. thermo-mechanically affected zone (TMAZ) and stir zone (SZ) microstructure, shown in Fig. 32 [205]. Dynamic recrystallization (DRX) of aluminium and magnesium grains were described in the weld nugget zone (WNZ) where the weld grain size is decreased as compare to the base metals i.e. below 18 µm was perceived because of higher stirring action taken place during FSW [58,60,79,83]. Grain size refinement and the occurrence of brittle IMCs makes a general fashion of decrease in ductility and increase in an average hardness value in the weld region as compared to workpiece. The detail discussion of the microstructural region is addressed in the next subsections.

7.1. IMCs analysis

The brittle and hard IMC thin layers are described to produce either at the lamellar shear bands or at joint interface in the weld nugget zone (WNZ). The IMCs layer thickness observed in the range of 1 µm–3 µm [64,81], whereas it has been reported that the IMC layers thickness below 10 µm and above 1.5 µm may be categorised as good and defects free weld [120,121].

Kostka et al. [64] also reported that the appearance of nano-sized grains of Al13Mg2 phase developed in close vicinity to the Al12Mg3,7 IMC phase layer indicating the presence of both IMCs brittle phases, which is also reported by var-
Fig. 33 – Intermetallic compounds observe at various Al-Mg FSW interface (a) fine-grained Al12Mg17 IMC splits the Al-6040 alloy (left) from Mg-AZ31 alloy (b) presence of small grains (nano-sized) of the Al3Mg2 phase adjacent to the Al12Mg17 (c) SEM from different cross sectional areas in Mg-Al lap joints (d) and (e) SEM BSE images of IMC transverse cross section of a lap weld [2,64,69].

rious researchers. Nevertheless, the IMC phase Al12Mg17 is usually found more comparing to IMC phase Al3Mg2. Concerning with what Yamamoto et al. [67] identified previously but energy-dispersive X-ray spectroscopy (EDS or EDX) examination pointed out that the FSW of aluminium-magnesium weld certainly undergo through constitutional liquation and produces various IMCs upon cooling [60,61,69]. Moreover, Al12Mg17 phase IMC may have favourably formed as a result of its lower eutectic temperature [83]. The various IMCs phases obtained during Al-Mg FSW at interface, is shown in Fig. 33(a–e). It is very crucial to maintain the peak temperature in order to avoid the IMCs formation to some extent. Therefore, it is very interesting and needful area of research to find the optimum set of parameters to get off the IMCs problem.

7.2. Tensile strength or joint efficiency

One of the most common weld quality analyses is mechanical characterisation such as; hardness and tensile test. Joint efficiency (\(\eta\)) is a term to express the joint quality and it is defined as the ratio of joint tensile strength to the base metal tensile strength. From various reports, it can be concluded that, a higher joint efficiency can be attained with optimum welding parameters despite of dissimilar workpiece. However, fracture location generally occurs at the joint interface and the fracture surface gives the clear evidence of presence of IMCs which shows detrimental effect on the joint quality. Moreover, the percentage elongation of weld is considerably lesser as compare to base metals; approximately 2% shows at the weld interface [16,63]. The main reasons of being low elongation value are studied by Pourahmad et al. [75], Liang et al. [76], and Azizieh et al. [83] whereas; maximum percentage ductility was 4.5%, 6% and 9%, respectively. The stress-strain curve, percentage elongation and tensile strength of Al-Mg alloy are shown in Fig. 34(a–c) [75,76,83]. In the previous case, enhancements were supposed to occur because of the post weld heat treatment of about 1 h at 320 °C temperature. Post weld heat treatment of dissimilar metals would lead to a new set of residual stresses due to difference in thermal expansion coefficients of Al and Mg. However in this study, the tensile strength was improved after heat treatment. Because the difference between the thermal expansion coefficients of Al and Mg is not much, the increase of tensile strength could be attributed to the effect of more stress relief than the generation of new stress for 1 h post heat treatment. Even though, it does not seem to be a good compromise, as the joint efficiency was roughly 19% with tensile strength of 36 MPa only [75]. On the other hand Liang et al. [76] perceived better percentage elongation once the fracture location shifted to Al alloy HAZ area from the weld interface, where fracture after necking formation was detected. The reason for the shifting of fracture location is unclear, but microstructure of sample cross section seems to show a weld interface of Type 3 (refer Section 3.2).

On account of the large interpenetrating feature (IPF) and complex geometry the strain while loading may have been homogenously dispersed to permit material deformation on soft HAZ alloy to start the first yield. No clarification was mentioned for higher elongation stated by Azizieh et al. [83], but possibly this may also because of the formation of Type 3 bond interface. To obtain as high tensile strength (joint efficiency) as base metal and keeping the IMCs formation as low as pos-
7.3. Hardness variation

The variation in average hardness value is mainly dependent on three factors, i.e. material flow, process temperature, and rate of strain [16]. Also depends on the distribution of magnesium particles in aluminium matrix throughout the welding process [45]. Higher volume fraction of IMCs particles also enhances the average hardness of nugget zone (NZ). The most conceivable reason for higher hardness on any weld section is: (i) presence of higher IMCs volume fraction and, (ii) relatively higher distribution of fine lamella structure. As validated by Stathers et al. [206], hardness assessment is a consistent characterization technique for calculating the tensile strength properties (i.e. yield and ultimate tensile strength) in the heat affected zone.

Higher heat generation occurs at higher rotational speed, lower welding speed [48,49], higher shoulder diameter [54], and higher tilt angle [175] which resulting into higher IMCs volume fraction and higher average hardness in stir zone [13,93]. Strengthening phenomenon due to IMCs formation significantly increases the hardness value [93,138]. Various hardness profiles has been mentioned by several researchers for Al-Mg joining through FSW are presented in Fig. 35. The maximum hardness value was noticed at Al-Mg weld line which was probably a result of grain refinement, solid solution strengthening, dynamic recrystallization and mechanical twinning. This greater hardness is also because of the Al12Mg17 phase IMC existence. The nano-sized grains (recrystallized grains) are mostly established in centre of the weld nugget zone (WNZ) and by this reason maximum hardness value is located in same region, shown in Fig. 35(a–h). Singh et al. [207] observed the complex material flow behaviour and this was the main reason for maximum microhardness levels in WNZ. The hardness of WNZ is always higher comparing to the base metals due to the presence of brittle IMCs and fine grain size after substantial plastic deformation. The hardness level distribution is found to be heterogeneous for Al − Mg butt joint arrangement, shown in Figs. 35(b, g and h). Hardness levels differ not only in various weld regions but also from top to bottom along weld thickness. Fabrication of Al-Mg workpiece through FSW with appropriate ductility (i.e. lower hardness) in stir zone is an interesting and much demanding area of research and need to be explored significantly.

7.4. Various defects and failure mechanism during FSW of Al-Mg

Selection of inappropriate welding parameters or a wrong welding strategies leads to several welding defects. Radiographic testing is used to perceive the blind defects in the FSW weldments [88,89]. Among all associated defects, the most
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Various defect</th>
<th>Origin location</th>
<th>Root cause</th>
<th>Image of various defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kissing bond defects</td>
<td>Stir zone interface</td>
<td>(i) Oxide layer removal from faying surface; (ii) Higher welding speed; (iii) Insufficient material flow</td>
<td><img src="image" alt="Kissing bond" /></td>
</tr>
<tr>
<td>2</td>
<td>Tunnelling defects</td>
<td>On advancing side between the SZ and TMAZ under the weld surface</td>
<td>(i) Lower plunge depth; (ii) Higher welding speed; (iii) Inappropriate tool pin offset; (iv) Lower rotating speed; (v) Wrong tool design selection.</td>
<td><img src="image" alt="Tunnel" /></td>
</tr>
<tr>
<td>3</td>
<td>Void/cavity defects</td>
<td>On AS of the weld, and below the weld surface</td>
<td>(i) Too high traverse speed; (ii) Inappropriate forging load; (iii) Inappropriate tool tilt angle.</td>
<td><img src="image" alt="Void defect" /></td>
</tr>
<tr>
<td>4</td>
<td>Lack of Penetration defects</td>
<td>Beneath the stir zone at the joint interface</td>
<td>(i) Local variations in the plate thickness; (ii) Inappropriate tool design; (iii) Incorrect plunge depth; (iv) Very short pin length.</td>
<td><img src="image" alt="Lack of penetration" /></td>
</tr>
<tr>
<td>5</td>
<td>Hooking defects</td>
<td>Advancing side of TMAZ and retreating side of lap welding</td>
<td>(i) Lower welding speed; (ii) Higher rotational speed; (iii) Inappropriate tool design; (iv) Improper tool tilt angle.</td>
<td><img src="image" alt="Hooking defect" /></td>
</tr>
</tbody>
</table>

Table 5 – Common friction-stir welding defects: [3,28,35,69,75,76,87,160,203,208-232].
Table 5 (Continued)

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Various defect</th>
<th>Origin location</th>
<th>Root cause</th>
<th>Image of various defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Flash defects</td>
<td>Around the tool-pin and tool-shoulder</td>
<td>(i) Excess heat input; (ii) Lower welding speed; (iii) Higher rotating speed.</td>
<td><img src="image" alt="Flash defects" /></td>
</tr>
<tr>
<td>7</td>
<td>Macro &amp; micro crack</td>
<td>Bonding surface to stir zone depth</td>
<td>(i) Unsuitable pin offset; (ii) Lack of material flow; (iii) Low heat input; (iv) Stress concentration in weld</td>
<td><img src="image" alt="Microcracks" /></td>
</tr>
<tr>
<td>8</td>
<td>Fragmented defect</td>
<td>Stir zone(SZ)</td>
<td>(i) Improper tool pin eccentricity; (ii) High rotational speed.</td>
<td><img src="image" alt="Steel fragment" /></td>
</tr>
</tbody>
</table>

fundamental defects which are considered during dissimilar FSW are mentioned in the Table 5 [3,75,209]. Considering the kissing-bond defects, this is occurred as a result of ineffective material stirring due to insufficient compressive force from tool which appears in the TMAZ and SZ interface. This defect is considered as an extension of the hooking defect in the TMAZ. In hooking defects, the weld thickness was much thinner comparing to normal welding. In such defects, there is almost negligible metallic bond occurs in welding zones of the base materials [210,211,235,236]. It should be noted that the kissing-bond is perceived only in the retreating side of the joint. To evade this defect, comprehensive material intermixing during FSW is necessary by providing proper material flow around the tool pin [211–213]. On the other hand, tunnelling defect is a very common type of defect in friction stir welding, which also considerably affects the weld mechanical properties. Balos and Sidjanin [214] studied the tunnelling effect and reported that how this defects decreases the mechanical properties by 25%–82%. This kind of defects usually appears at advancing side of the workpiece between the WNZ and TMAZ.
Like other FSW defects, this is also taken place due to inappropriate welding parameters selection such as: welding and rotatory speed, improper tool design and tool offset [215,216]. The tunnelling defect can be eliminated or minimized by adequate heat input and its distribution on either side of the weld zone and appropriate material flow intermixing behind the probe [217,218].

In addition to this voids and cavity defects are usually found at the advancing side of the weld and they may or may not break comprehensively to the weld surface as mentioned.
in Table 5 [219]. The formation of voids and cavities may occur due to the very low tool rotational speed. The presence of voids strongly leads to reduction in ductility and somewhat the weld strength also. Higher traverse speed and lower rotational speed results in insufficient material flow and heat generation [210,219]. To eliminate such defects, an optimum welding and rotational speed should be selected. Furthermore, the most frequent occurring defect is lack of penetration. This defect generally found due to a short tool plunge depth or pin length or both may cause a bottom section of the weld root to remain unstirred, which exhibits as incomplete weld root penetration. When it is subjected to a load, the joint may deteriorate along the weld line. This defect may also appear due to the unsuitable tool probe offset, uneven sample thickness, improper abutting plates setting and incorrect tool configuration [211]. To eradicate this defect, complete intermixing throughout the weld root is necessary by giving suitable pin length and tool plunging depth so that stirring action can be done even the bottom most part of the sample, however keeping in mind that the pin tip will not touch the backing plate. By the existing literature, it is advised to choose 0.1-0.3 mm shorter tool pin as compared to plate thickness [210,220,224]. In addition to the defects list, hooking defect is also a considerable FSW defect, which appears only in the thermo-mechanically affected zone (TMAZ), adjacent to the weld nugget region. This defect might not appear in the heat affected zone (HAZ), since this region is only affected from the heat of TMAZ region [213,226,232].

The other considerable defect is flash defect. This defect is generally occurred by excessive heat input, which plasticae the weld material near tool-shoulder region and ejects huge volumes fraction of soft material in the form of weld flash. However, if the pin plunge depth is higher, the soft material adjacent to the pin is extruded. Therefore, the suitable pin length selection becomes very crucial to avoid such defects in FSW [221–229]. Whereas, high stress concentration leads to crack formation has also been conveyed in the various existing literature. Though not as critical as in various conventional fusion welding processes, confined melting during FSW and the following cooling would cause hot surface cracking at high stress [35,69,76,87,208,222,223,230]. These surface cracks are also believed to be occurs due to crack initiation and accelerate through mechanical interlinking. Cracks may be in the form of macro or micro level. Micro-cracks are seen only by the high resolution radiographic testing like TEM and SEM. To evade this problem, heat input and its distribution is the key factor to control such defects during FSW.

Considering various defects in dissimilar FSW, fragmented defects also comes under main defects. These are exceptionally found during welding of Al-Mg, Al – Cu and Al-steel through FSW and usually do not observe for similar material FSW. The hard IMCs fragments scattered in the Al matrix are deliberated as fragmented defects. The uneven material flow unable to dispense these hard particles uniformly, thus these fragments and sharp edges makes the weld region remains unfilled and leads to form voids and microcracks. Optimum welding parameters mainly the appropriate tool pin eccentricity and lower rotating speed can eliminate such types of defects [160,222,224,227,234]. Selection of optimum welding parameters and proper setup are the crucial factors to get a defect-free and sound quality dissimilar Al-Mg joint. At present and to the authors’ concern, none of the researchers has been reported any work to measure the residual stresses precisely for fabrication of Al-Mg alloys through FSW, which may be a feasible area of research in future.

8. Applications

The applications of aluminium-magnesium alloys fabricated through the FSW have been reported in various literatures and the main components in various sectors are as summarized below: [51,53,59,63,67,74,79,82,104,114,126,150, 186,192,211,215,220,228,229,233,237].

(i) Automobile sector: wheel rims, engine chassis, truck bodies, car frames and fuel tankers.
(ii) Aerospace sector: Wings, fuselages, aviation fuel tanks, cryogenic tank.
(iii) Railway sector: Container bodies, goods wagons, carriages and trams.
(iv) Shipbuilding and marine sector: Marine and transport structures, helicopter platforms, panels for deck and floor, masts and boom for sailing boats, offshore accommodation.

9. Upcoming perspective and outlook

The friction stir welding has been found a greater use in aerospace, automobile, marine and railways industries over advancement in material development estimations, equipment intelligence, structural designs and testing programmes, tooling and process parameters innovations. There is several points still need to be addressed in upcoming research for dissimilar Al-Mg FSW:

(a) The internal residual stresses set up during mechanically and thermally induced loads applied can be decrease by selecting appropriate process variables and by using post weld heat treatment (PWHT). Therefore, these are the interesting and much needed future research in this domain.
(b) Mostly, lap and butt joint configuration have been reported through FSW. However, it requires much perfection for other weld configuration also like real structural design.
(c) Various variants of FSW would be a possible solution for suppressing IMCs formation namely; back heating assisted welding, cooling assisted FSW (CFSW), stationary shoulder, laser-assisted FSW, reverse dual-rotation FSW (RDR-FSW), and ultrasonic-assisted FSW.
(d) The material flow behaviour is the very critical and complicated phenomenon during FSW and still it requires more understanding.
(e) The research works revealed that post-weld heat treatment (PWHT) intensely decrease the intergranular corrosion depth after friction stir welding. To the authors’ knowledge, corrosion behaviour of Al-Mg fabricated through the FSW has not much studied therefore, a proper study and analysis need to be done in this area of research.

The FSW of very thin i.e. micro friction stir welding (thickness less than 1 mm) has a vast application in several industries (mostly in electronics, automobile and aerospace industries), which shows a good future scope for the researchers with reliability.

10. Conclusion

Combination of aluminium and magnesium are having potential to use in multi-material structures. Therefore, various studies concerning dissimilar material i.e. Al-Mg joining through FSW have been discussed. This paper aims and reviews the on-going advancement and progress in FSW of Al-Mg alloys. Despite substantial research work in the field of dissimilar Al-Mg FSW is available, an in-depth investigation for joining these materials is still absent and therefore, subsequent conclusion has been given for upcoming research.

1 The coefficient of friction between tool and work material has not considered anywhere and still this topic is uncovered, as this will help to find out the exact heat input during FSW.

2 A proper selection of tool shoulder and pin geometry may improve the material flow behaviour in the stir zone. Particularly, by using threaded pin enhances the joint efficiency with adequate material flow. Some other available tool geometry is to be considered like; concave and flat shape for shoulder and pin respectively. Tool selection with respect to workpiece material and its thickness is very much essential.

3 Prevention of excessive heat input by applying cooling system has shown tremendous enhancement in joint reliability due to the suppression of IMCs growth. Various approaches for cooling assisted FSW need to be promoted for future work.

4 The increase in hardness over weld zone is directly influenced by grain refinement and solid solution strengthening. Post weld heat treatment (PWHT) method will be a potential technique to improve the weld grain structure so that it will enhance the weld strength.

5 Material flow stress and temperature distribution with inappropriate set of parameters leads to a detrimental effect on weld quality, which requires special consideration in upcoming research.

6 No comprehensive data are available regarding electrochemical corrosion analysis of Al-Mg joint through FSW; it is an important topic of consideration and requires proper examination.

References

[21] Xie GM, Ma ZY, Geng L. Development of a fine grained microstructure and the properties of a nugget zone in

Disclosure statement

No potential conflict of interest was reported by the authors.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2020.01.008.


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