Repairing of exit-hole in dissimilar Al-Mg friction stir welding: process and microstructural pattern

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Abstract

The exit-hole is one major discontinuities in the friction based processes, where all the volume of the tool's probe is missing with a depth that corresponds to the full thickness of the processed component. This letter presents a new technique to repair the exit-hole of an Al-Mg friction stir welding, without any third body material with inexpensive probeless tooling, inducing forging, stirring, and thermomechanical consolidation of the local spot joint. Intercalated banned type structures with interpenetrating features were achieved. Composite type mixed structure was obtained at repaired zone with a local tensile strength of 159 MPa.

Keywords: exit-hole; friction stir welding; microstructure; repairing; welding

Introduction

The start and end zones of any welding process are characterized by transient thermophysical conditions that are different from the quasi-stationary state of the welding procedure specification. This phenomenon yields a local geometrical discontinuity that depending on the specified level of quality it may, or not, be tolerable. In friction stir based techniques, the exit-hole, left open by the probe, during the extraction phase, is a major geometrical discontinuity, where the local mass reduction through the thickness is significant. Examples of friction stir based techniques wherein the exit-hole is noticeable are the friction stir welding (FSW) [1-3], friction stir processing (FSP) [1, 4] and friction stir spot welding (FSSW) [4, 5]. There are some proposed methods to deal with this exit-hole, but the lack of an efficient and easy to implement solution results in that typical industrial approach to manage the exit-hole is to remove it by extracting that particular portion from the structure. This leads to material waste with secondary cutting operational cost and processing time.

Conventional method to deal with start and end conditions in FSW is with run-on and run-off tabs that are placed before welding and extracted after welding [6], whereas the advanced processes to heal the exit-hole without extraction of material are the friction bit joining [7-9], friction forming [10], refill friction stir welding [11-12] and modified friction stir clinching (MFSC) with protuberance-keyhole levelling [13, 14]. Friction bit joining uses specially designed consumable bit to repair the exit-hole [7-9]. Friction forming is developed for exit-hole of FSSW, which fills the cavity of exit-hole with extrusion of material from the revert side of workpiece [10]. Refill FSW is developed with facility of clamp ring and sleeve for tool axial movement, wherein, tool probe moves material upward at the time of retraction phase to fill the exit-hole. MFSC protrudes the material during first stage while fills the exit-hole by subjecting protruded material inside the cavity of exit-hole in the second stage [13, 14]. These processes are attempted for similar workpiece materials such as aluminum, magnesium, and steel based materials, with great complexity and set-up cost.

Repairing of dissimilar FSW exit-hole was attempted in limited literature. Dissimilar Al-steel FSW exit-hole was repaired in case of lap joint configuration [15]. The secondary operation with circular path of tool was performed around the exit-hole. However, this technique is very challenging with butt joint configuration due to material mixing dissimilarities. Dissimilar ZEK 100 Mg - DP 600 steel FSSW was processed for its exit-hole removal by refilled FSSW using probe and sleeve mechanism [16]. They reported Mg and Fe interface with better bonding after refilling the keyhole portion. Despite of available articles on repairing techniques for FSW exit-hole, it is worthwhile to develop an efficient, easy and economically feasible solution to perform exit-hole repairing. In this investigation, the exit-hole of dissimilar Al-Mg FSW was repaired with the help of probe less tools with an interesting material mixing features.

Materials and Methods

Dissimilar FSW was performed on 6061 Aluminum alloy and AZ31B magnesium alloy as per process conditions of Mehta et al. [17]. Fig: 1 shows novel procedure to repair exit-hole of dissimilar FSW. The exit-hole of Al-Mg weld was repaired by two non-consumable probe less tools. In this work, the best set of process parameters was used after feasibility experiments. The repairing tools were plunged with rotational speed of 1070 rpm and plunge rate of 3 mm/min in both cases. The tool diameter was kept bigger than exit-hole diameter so that the bottom surface of tool makes contact with surface of workpiece that in turn fills the cavity of exit-hole by material deformation and subsequent vertical movement. Two different tools were designed in order to fill 6 mm deep cavity of exit-hole as shown in Fig: 1 (b) and (c), which were having their diameters as 15 mm and 21 mm respectively. A new exit-hole was left after two stages of aforementioned repairing, which was having around 1 mm depth and 21 mm width. This new exit-hole can be further settled with grinding and finishing operations.

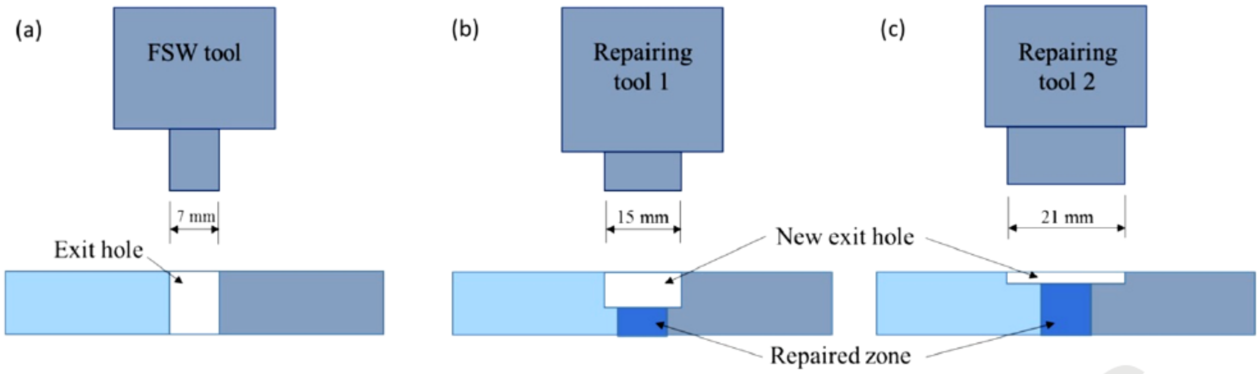

Fig. 1 Process: (a) FSW exit-hole, (b) Repairing phase 1, and (c) Repairing phase 2

The repaired zone is subjected to visual inspection, metallographic testing, microstructures and tensile strength in order to assess the soundness of the zone. The metallographic testing was carried out using standard procedure with grinding and polishing on carbide papers followed by etchant of hydrofluoric acid in water solution. The tensile specimens were prepared with the help of wire-cut EDM operation as per ASTM-E8 standards.

Results and discussions

Fig: 2 shows surface of exit-hole before and after its repairing. It can be seen from surface inspection that a deep cavity of exit-hole is satisfactorily repaired without any surface defects. Fig: 2 (b) is showing new exit-hole having its large width of 21 mm and very small depth of around 1 mm. This was further processed by grinding and finishing.

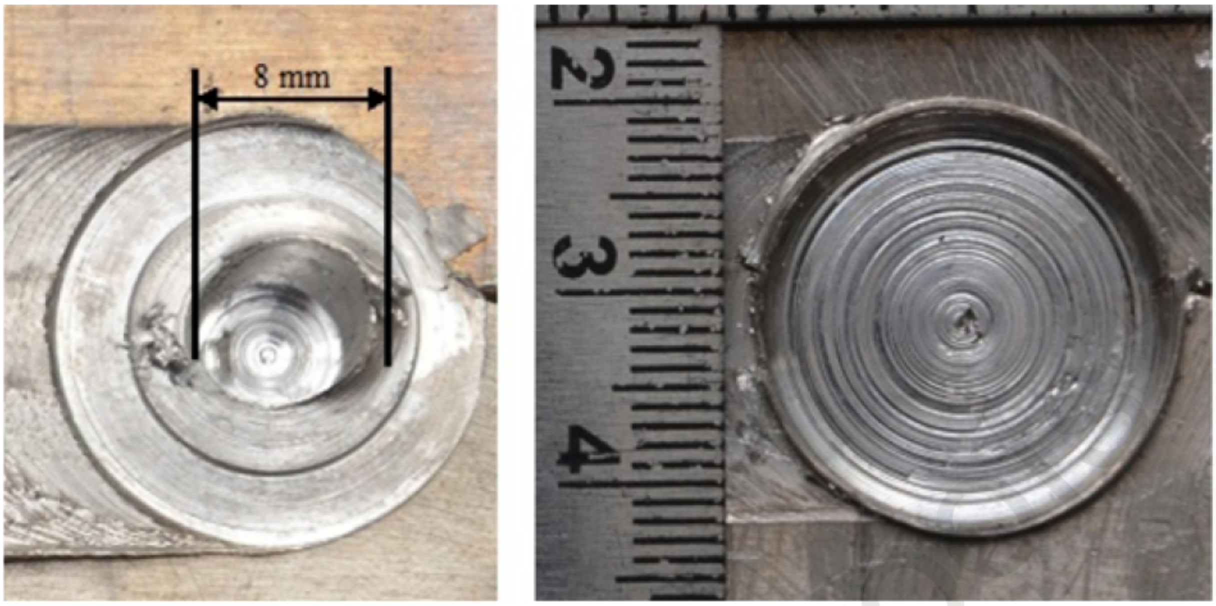

Fig: 2 Surface morphologies of (a) exit-hole and (b) repaired zone

Fig: 3 shows material mixing and microstructures of exit-hole repaired portion. It can be seen that the material mixing is very complex and unique considering Al-Mg welding. The bottom portion in the vertical cross section can be observed more complex as revealed by different features. There was no severe grain refinement observed unlike stir zone of FSW (refer Fig: 4) as stirring was not present and heat input was not adequate that induce grain growth after severe plastic deformation. The repaired zone of exit-hole was consists of interpenetrating features and lamellar structure, which was recommended as desirable structures of Al-Mg FSW [18]. It is suggested that combined action of rotation and forging resulted a drastic crushing action of workpiece material beneath the tool surface caused by plastic deformation. This in turn directed a deformed material towards bottom portion when tool: 1 was subjected. Intriguing features of intercalated banned type structures can be observed in the bottom portion. The intercalated microstructure of Al–Mg repaired zone was caused by distinct deformability behavior of Al and Mg and severe deformation during forging and swirling of Al and Mg. The vortexes and swirling were caused due to rotation and axial pressure that in turn resulted in helical material movement in axial direction. Due to this the lamellar type strips of Al and Mg were observed. These structures are consisted of large Al and Mg solid solution particles along with its reaction layers of intermetallic compounds (IMCs). The diffusion layer with formation of IMCs (with phases of Al_3Mg_2 and $Al_{12}Mg_{17}$) and Al-Mg and Mg-Al solid solutions in the stir zone were identified in the same sample [17]. Similar phases can be expected in the repaired zone with solid state diffusion and constructional liquation mechanisms. These type of diffusion layers are usually found at reaction zones where the elements of Al and Mg are interacted. The amount of deformation was less in case of tool: 1 compare to tool: 2 as tool: 1 was having smaller diameter than tool: 2. In case of tool: 2, the same phenomenon of material mixing in vertical direction may have resulted with larger heat input. However, the top portion filled in repaired zone was without such complex features as larger diameter may have allowed more intermixing than bottom portion (as can be evidenced from Fig: 3 (a, b, c, d, f and g)). The intermixing of Al and Mg was evidenced by elemental mapping as can be seen from Fig: 3 (i) performed in between top and bottom portion of repaired exit-hole. The microstructures also reveal that the joining mechanisms were like mechanical interlocking with tortuous interfaces of Al and Mg particles with intermixed structure and matrix of Al and Mg at different portions along with obvious chemical bonding of IMCs (phases of Al_3Mg_2 and $Al_{12}Mg_{17}$ are expected based on stir zone studies [17]).

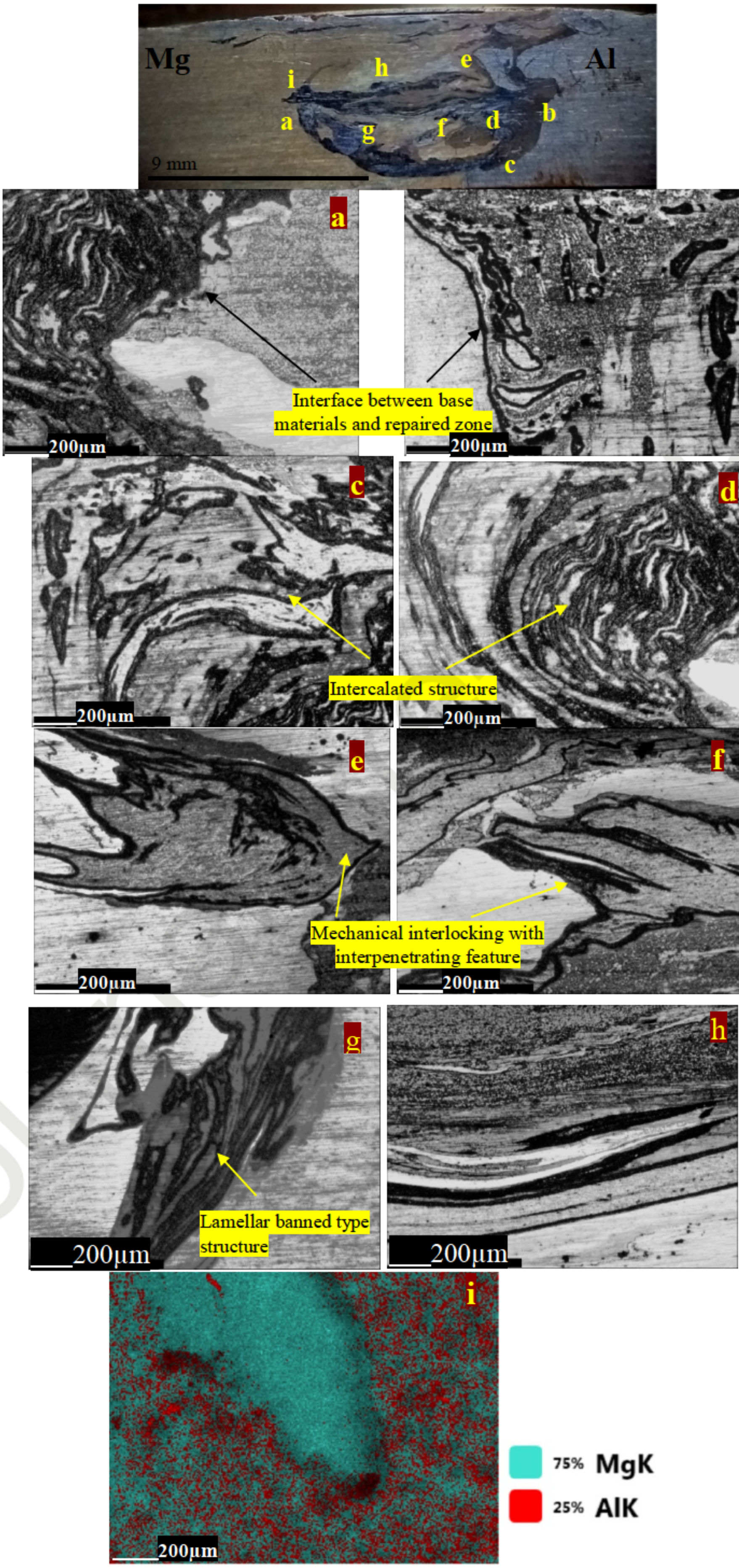

Fig: 3 Material mixing and microstructures of dissimilar Al-Mg exit-hole repaired portion

Besides, Fig: 4 shows microstructural features of the stir zone of Al-Mg FSW. Dissimilar materials Al and Mg are mixed together due to stirring action followed by material movement like onion rings that typically found in FSW. Obvious interface between Al-stir zone-Mg are distinguishable [Fig: 4 (a, c, d and e)] with each other, and also different than the repaired zone. Intercalated lamellar structure can be found at many instances in Fig: 4, however, totally different than repaired zone of Fig: 3. Localized stirring led to small size detachment of both the materials that are mixed after intense swirling action with stretched grains in the direction of stirring action [Fig: 4 (a, c and d)]. Variations in deformation behavior lead to different sized detachments of both the materials [Fig: 4 (b, e and f)] that are intermixed after swirling, forging and movement in transverse direction.

The material mixing was found as intriguing result as far as dissimilar Al-Mg exit-hole repairing is concerned. The excellent material mixing is cross verified with tensile strength of repaired portion. Ultimate tensile strength of 159 MPa was obtained when exit-hole repaired portion is subjected for tensile testing. The obtained tensile strength was 124 % overmatching relative to dissimilar Al-Mg FSW [17], whereas the same was 63.6 % of the base material of AZ31B, which can be considered as acceptable for Al-Mg dissimilar joining. Heterogeneity in material mixing and formation of IMCs are leading reasons for slightly less tensile value compare to base material, as these IMCs are prone to form cracks due to their brittle nature. These cracks may have formed in very small size (as that was seen in optical micrographs), which may be the reason for low tensile strength of repaired zone. The exit-hole repairing was successful with unique features of material mixing and acceptable tensile strength.

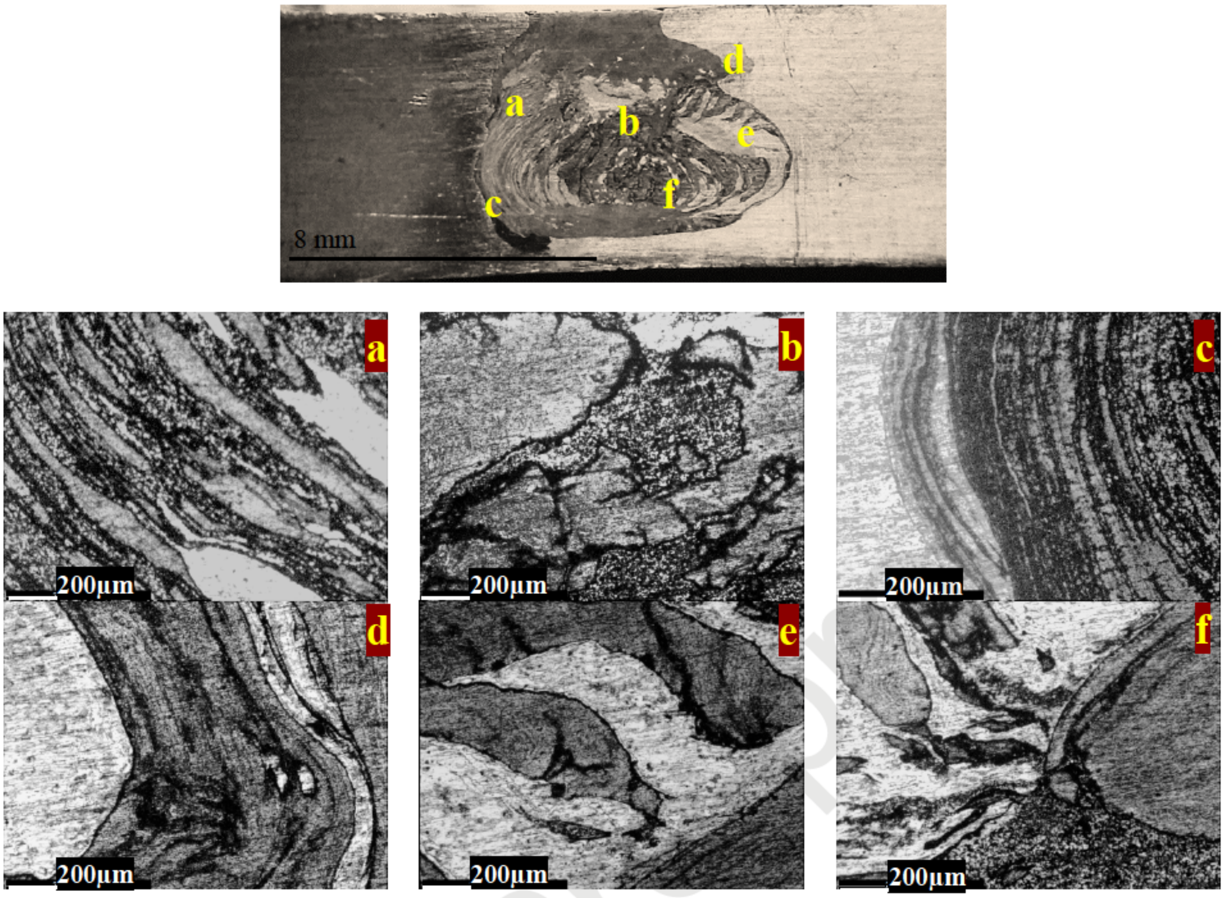

Fig: 4 Microstructural features of dissimilar Al-Mg friction stir welded stir zone

Conclusions

The successful application of exit-hole repairing new technique of probeless tools to a dissimilar Al-Mg FSW joint shows the robustness of the innovation. The proposed new technique uses inexpensive probeless tools without any complex features for thermomechancial consolidation caused by axial forging and frictional deformation of material surrounded by the exit-hole itself. Intrigued material mixing with substantial features of intercalated banned type structures with interpenetrating features were observed after exit-hole repair. Composite type mixed structure of Al and Mg materials was obtained at repaired zone with tensile strength of 159 MPa (124 % overmatching to the conventional Al-Mg FS welded zone).

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- First investigation of Al-Mg FSW exit-hole repairing with novel processing of pin less tools
- Intercalated banned type structures with interpenetrating features were observed at the repaired zone.
- Composite type mixed structure of Al and Mg materials was obtained at repaired zone with tensile strength of 159 MPa.