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ORIGINAL ARTICLE

# Microstructure and mechanical properties of the dissimilar welded joint of aluminum and magnesium alloys- a review

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## Abstract

The effective metal joining technique of friction stir welding (FSW) creates high-quality welds of incompatible alloys, which are highly challenging to fuse using the conventional fusion method. Due to their lightweight, high specific strength, elasticity, low density, and several other qualities, FSW of dissimilar Aluminum (Al)-Magnesium (Mg) and related alloys are urgently needed in various industries, including automotive, shipbuilding, and aerospace. The purpose of this study is to evaluate previous research in the area of dissimilar Al-Mg friction stir welding. The investigative approach is covered by outlining the joining process, heat production, and difficulties experienced during Al-Mg unification. In addition, patterns in phase evolution, microstructural evolution, mechanical characteristics, tool design, and hypotheses relating to the creation of intermetallic compounds (IMCs) are examined. Finally, this work recommends future options for welding Al-Mg alloys utilizing FSW, highlighting the most critical findings of earlier studies. 

## 1. Introduction

Utilizing lightweight materials with exceptional qualities is essential in today's industrialized and modernized society. As a result, Al, Mg, and their alloys are widely employed in various sectors (including automotive, shipbuilding, aerospace, etc.) due to their superior utilization and lightweight, high specific strength, elasticity, and other qualities. These metals and alloys are combined using various welding procedures to get the most satisfactory results possible. Welding has long been the most popular technology in several industrial areas due to its superior advantages over other joining processes. Although most metals are fused using various welding techniques, dissimilar welding of Al-Mg provides a particularly challenging scenario due to multiple metallurgical considerations [1,2]. This has sparked substantial study into different welding metals. By using traditional fusion procedures, it is exceedingly challenging to fuse different Al-Mg alloys because doing so results in the development of massive intermetallic compounds (IMCs), which significantly impact the mechanical characteristics of the weld [2,3]. Various researchers in their literature have put forth three approaches to prevent the production of IMCs: solid state welding to restrict welding temperatures; control of thermal history fluctuation in chemical reaction mechanism at the weld interface. [4-6]. FSW is therefore thought to be a superior solution for combining metals that are not the same. In light of the growing demand for Al-Mg alloys across many sectors, this review paper briefly outlines the numerous advancements and difficulties relating to FSW of different Al-Mg joints. The

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main topics of this article are the common joining process, welding settings and how they affect welded joints, microstructural observations, etc.

## 2. Intermetallic compound formation

Limiting the formation of brittle and hard IMCs layer at weld joint interface during dissimilar Al &Mg FSW is the biggest challenge as it deteriorates the strength and elasticity of Al & Mg joints. This problem is not only associated with FSW but is also associated with many other welding processes such as laser welding, diffusion welding, resistance spot welding etc. [7-9]. The brittle and hard IMCs at the weld joint interface of Al & Mg promote micro-cracks and stress concentration. IMCs formation is unavoidable and nearly impossible to prevent; hence the best approach is to minimize such compounds. Kerimeyer et al. claimed that a mechanically sound joint has an IMC thickness of less than 10μm [10]. However, Qiu et al. claimed that an IMC thickness of 1.5μm offers maximum joint strength during dissimilar FSW of Al & steel [11]. IMCs thickness is variable and keeps varying between 0.5μm to 1μm [12]. Different researchers claimed different theories for the evolution of IMCs in dissimilar FSW of Al & Mg. Still, the main ideas discussed in various literature to clarify the formation of IMCs are mainly based on diffusion bonding, mechanical/material interlocking and constitutional liquation or eutectic reaction mechanism [13, 14]. The preceding discussion concerns whether the peak temperature during FSW welding surpasses Al-Mg eutectic lines of 4500C (Aluminium dominant side) and 437°C (Magnesium dominant side). Yamamoto et al. attributed the structure and growth of such mixtures to a diffusion phenomenon caused by the temperatures below the eutectic line [15].

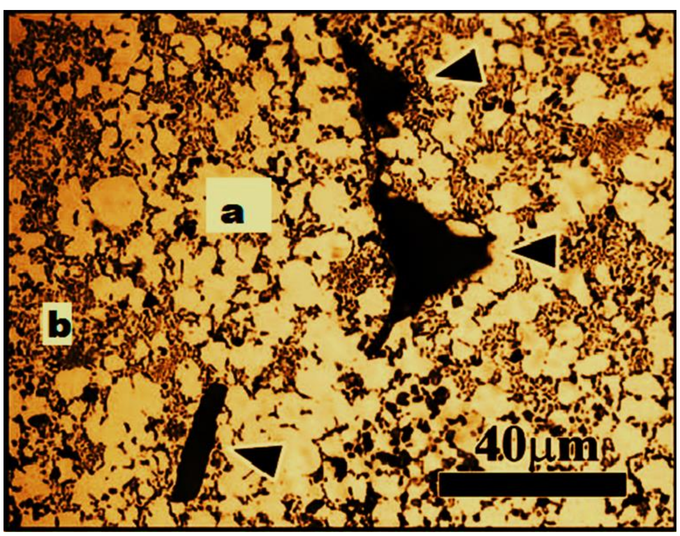


*Figure 1: Eutectic microstructure in Al1050 and AZ31weld performed at 1.5mm $min^{-1}$ and 2450 rev $min^{-1}$ [16]*

Most researchers, however, believe that the eutectic reaction is essential in creating IMCs between Al-Mg FSW. This eutectic reaction or constitutional liquation may cause solidification cracks in the welds. The constitutional liquation is the main reason for excessive IMCs in Al-Mg welds that are detrimental to their strength [17]. Fig. 1 presents the eutectic microstructure in Al050 and AZ31weld.

## 3. Rotational speed & Welding speed

The most critical and necessary FSW parameters are the rotational tool speed, ω (rpm), and welding speed or tool linear speed, υ (mm/sec), as these parameters significantly impact material input and heat flow. Higher rotating speeds result in higher heat input. Still, higher welding rates or welding speeds result in lower heat input because heat input is directly proportional to rotational speed and inversely proportional to traverse speed. These parameters need to be optimised to obtain the best quality of the weld [18-21]. The fracture position of the weld is also affected by rotational tool speed, which widens the strained area and shifts the most significant strain zone towards the advancing side (AS) from its original retreating side (RS) [22, 23]. Many researchers have reported the phrase "revolutionary pitch" as one of the primary and key parameters to generating quality welds based on both parameters' compounding influence. The ratio of welding speed and rotational speed (υ/ω) is known as revolutionary pitch [24-26]. Fast welding (cold welding) is represented by a higher revolutionary pitch, while a lower extreme pitch represents slow welding (hot welding). Higher pitch ratios are responsible for lower peak temperatures and insufficient material flow. In contrast, too low pitch ratios are responsible for poor material flow and higher liquation, which further encourages the formation of IMCs, deteriorating the weld quality [27, 28]. When rotational speed is low, it promotes low-temperature generation in the nugget zone, i.e. strengthening of particles is increased as shown in fig. 2(a) and 2(b). When this rotational speed is high, it leads to particle separation in TMAZ, as shown in fig. 2(c) and 2(d) [23].
According to different research articles, the revolutionary pitch ranging from 0.02 to 0.38mm/rev is considered favourable for dissimilar FSW of Al & Mg. The parameter that defines the joint quality is known as Joint efficiency. Joint efficiency is the ratio of the ultimate tensile strength (UTS) and base metal UTS with the lowest value (i.e. higher efficiency) in case of dissimilar welding. Rotational and traverse speeds also affect the macrostructure and weld appearance in dissimilar Al-Mg FSW [29]. Fig. 3 shows a different set of parameters and defects associated with them when Mg alloy was placed on the Advancing side during FSW. The Ultimate tensile strength (UTS) of the welds increases with increasing welding speed at constant rotational speed, as shown in fig. 3(a, b) [29]. Further, Yang C et al. reported an increase in elongation percentage with increasing welding speed, as shown in fig. 3(b) [27]. Elongation takes place due to the formation of IMCs and heat input. Heat input is inversely proportional to welding speed; hence, a lesser amount of heat input is produced at higher welding speeds. As a result of this, intermetallic compounds (IMCs) formation is significantly less hence making the Stir Zone (Stir Zone) less brittle [29, 30].

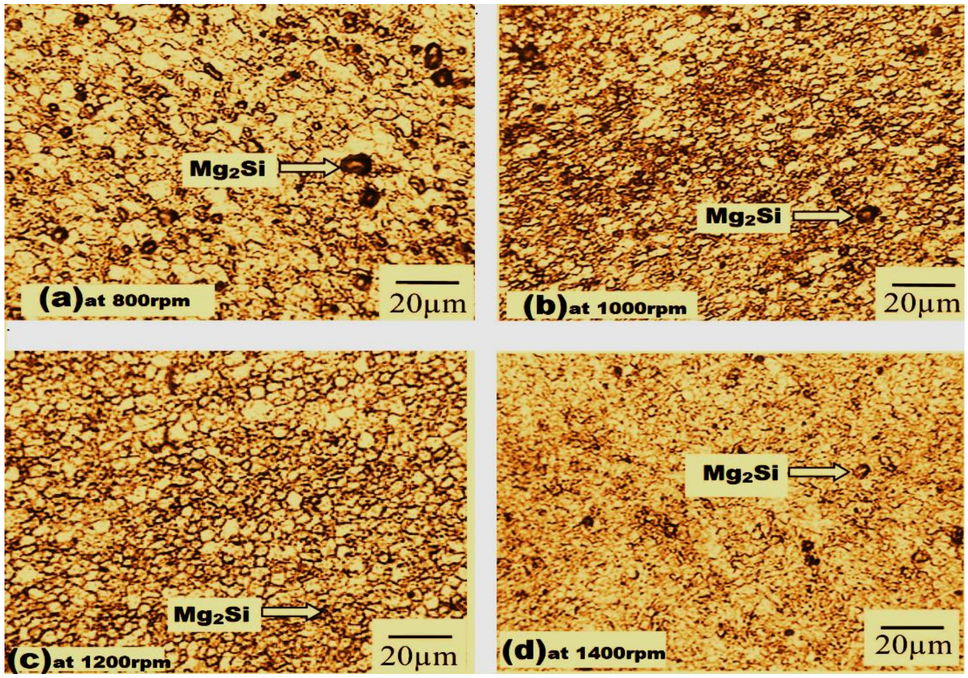


*Figure 2: Rotational speed effect on microstructure of Friction stir welding [FSW] zone at different RPMs. (a-d) [23].*

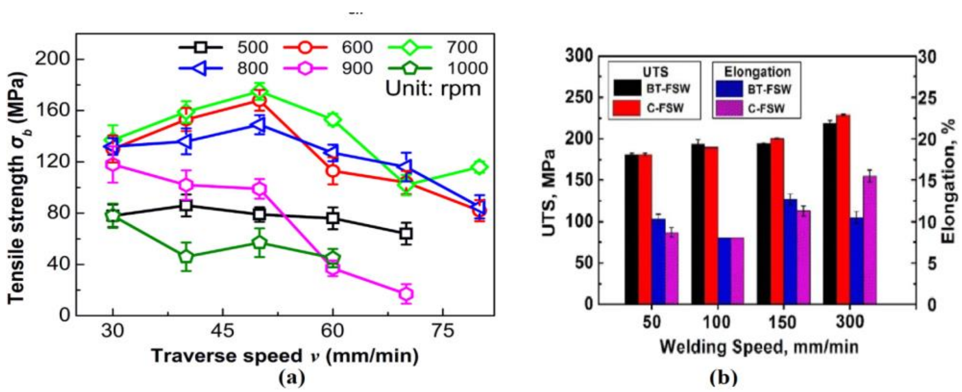


*Figure 3: (a) Graph showing variations in tensile strength with increasing welding speed and at constant rotational speed, (b) Graph showing percentage elongation and variation in UTS with increasing welding speed [29, 30].*

## 4. Peak temperature effect and cooling effect FSW

A large number of studies have reported the effect of peak temperature and cooling effect in one way or the other. The peak temperatures are measured using several thermocouples either inside the tool pin or into the sample. A K-type thermocouple on the bottom side of the job piece for peak temperature measurements was used [31]. The best strength was obtained at eutectic or peak temperatures between 430°C and 4600C. Further, they reported the effect of (a) peak temperature on stir zone (SZ) grain size, (b) IMCs and (c) hardness of the weld joint. The value of hardness and the amount of IMCs formation also increased in the weld nugget zone, but, on the other hand, lower welding and higher rotating speeds resulted in better corrosion resistance properties [29]. Firouzdor et al. stated that the Al must be placed at the advancing side to obtain higher peak temperatures and offset the tool towards the Al side [13]. The external water cooling methods during FSW of Al 5083 and Mg AZ31C-O to reduce peak temperature and obtain better weld quality [30]. When an underwater Friction stir welding (UFSW) method was developed and implemented on Mg alloy AZ31 and Al alloy 6013 [34, 35]. However, Miyamori et al. found that using Underwater friction stir welding (UFSW) on carbon steel resulted in higher torque and compressive force in the z-axis compared to traditional FSW because water cooling limits temperatures and increases the flow stress necessary for material plastic deformation shown in fig.4. During UFSW, the cooling rate is faster than in air because the specific heat of water is roughly four times that of air. A faster cooling rate suggests grain expansion in the heat affected, and the weld nugget zone is constrained. It's also worth noting that the rate at which weld cools varies from surface to surface, depending upon the thickness of the weld. According to Zettler et al. [36], the bottom portion of Al 6040 and Mg AZ31 alloy manufactured via FSW has a higher hardness value. The bottom surface shows quick cooling when compared to all other sample surfaces, most likely due to direct surface-to-surface contact with the backing plate, which acts as a heat sink [36].

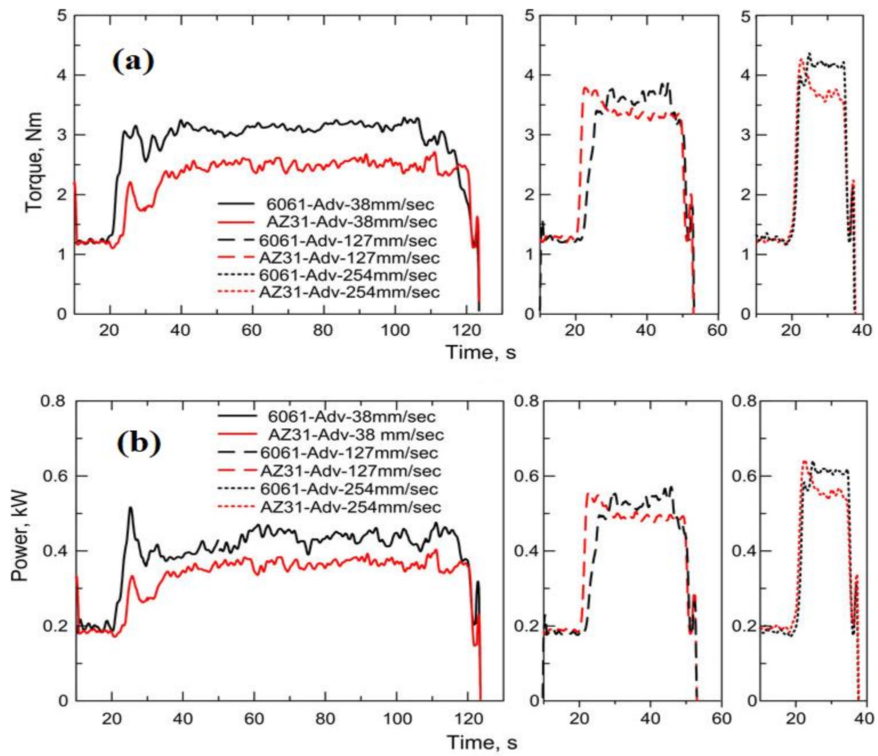


*Figure 4. (a) Torque Vs Time graph (b) Power Vs Time of dissimilar FSW of Al 6061 - Mg AZ31B at different travel speeds (in mm/sec) and at rotational speed of 1400rpm [13].*

## 5. Microstructural characterization in FSW of Al-Mg

The Base Material (BM), heat-affected zone(HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ), also known as nugget zone (NZ), are formed by plastic deformation and friction heating caused by the rotating and stirring impact of FSW tools. The welded junction's quality and characteristics are determined by each weld zone's microstructural features [37-40] The weld nugget zone and its surroundings are the subjects of microstructural characterization. Dynamic recrystallization (DRX) of Al and Mg grains has been observed in the nugget zone, where a reduction in grain size below 18μm compared to the parent metal is often observed due to the tool's stirring action [41]. Grain size refinement and the existence of IMCs increase the hardness and decrease the flexibility in the welding zone compared to the work piece.

### *5.1 IMCs Observation*

IMCs form either at the joint interface in the weld nugget zone or at lamellar shear bands. IMCs so formed are brittle, and their thickness ranges from 1μm to 3μm [42]. However, many studies claim that the IMCs thickness between 1.5μm and 10μm produces good quality defect-free welds [43, 44]. The development of nano-sized grains of the Al3Mg2 phase in immediate proximity to the Al12Mg17 IMC phase layer shows the presence of both IMC's brittle phases. Many other studies also claimed the same. However, compared to the $Al_3Mg_2$ phase, the $Al_{12}Mg_{17}$ phase is more prevalent. To avoid the development of IMCs, it is necessary to maintain peak temperatures up to some extent, which is not an easy task. As a result, choosing the best set of parameters to solve the IMCs problem is a fascinating and important research topic. Figures 13 to 15 depict the production of IMCs at the interface of Al and Mg alloys during FSW

## 6. Hardness and its variation

Hardness value mainly depends upon strain rate, process temperature, and material flow. Throughout the welding process, the dispersion of magnesium particles in the aluminium matrix is also significant. The hardness valuation is indeed a comprehensive characterization method for determining the properties of tensile strength, namely ultimate and yield tensile strength) in HAZ [46]. The hardness value substantially increases during the strengthening phenomenon due to the production of IMCs [47]. Different hardness profiles described by other authors in FSW of Al-Mg are shown in figure 19. The Al-Mg weld line had the highest hardness value, most likely due to mechanical twinning, grain refinement, recrystallization and solid solution strengthening. The presence of the Al12Mg17 phase IMC contributes to the increased hardness. Because recrystallized grains were predominantly found in the weld nugget zone (WNZ), the maximum hardness value was obtained there, as shown in fig. 19 (a–d). The complex material behaviour was noticed which was the fundamental explanation for the highest microhardness values in the weld nugget zone [48-52]. The hardness of the weld nugget zone is always higher than that of the base metals due to the presence of brittle IMCs and microscopic grain size after severe plastic deformation. The hardness degree of a weld varies not just between weld zones but also from top to bottom along its length. Welding aluminium with acceptable ductility (lower hardness) in the stir zone using the FSW method is an exciting and challenging subject of research that needs to be thoroughly researched.

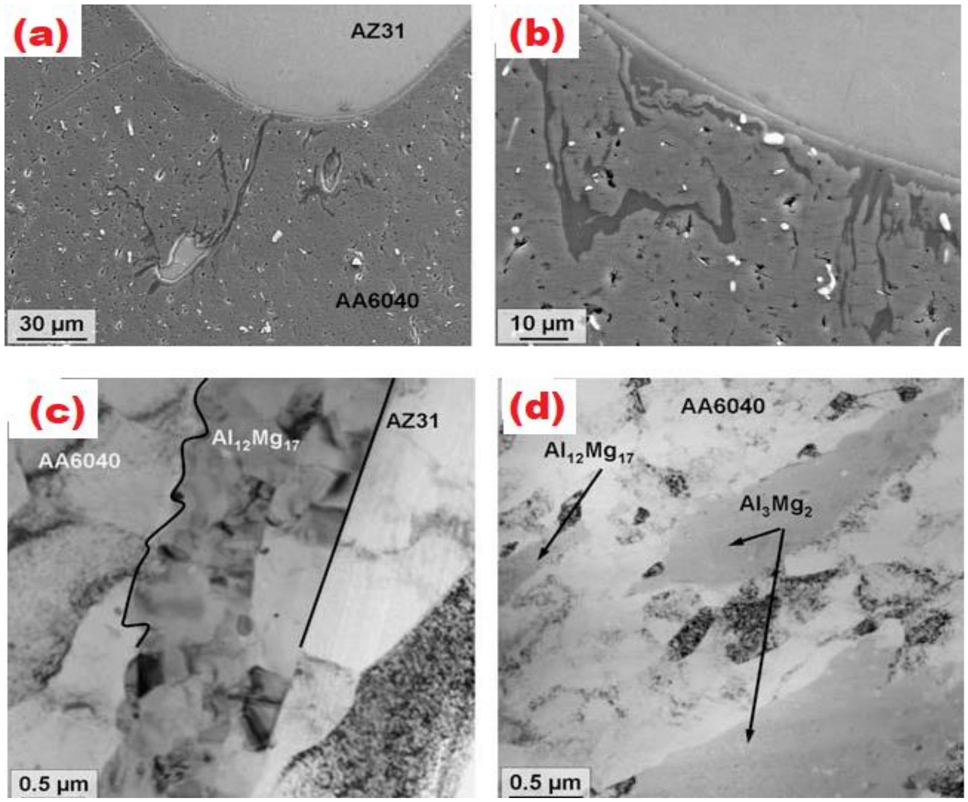


*Figure 5. (a) SEM images of Mg alloy AZ31 inclusion in Al alloy AA6040 and IMCs formation around it. (b)Enlarged view of IMCs so formed as described in earlier. (c) TEM image showing the separation of Al alloy AA6040 (left) from Mg alloy AZ31 by fine-grained intermetallic compound (d) TEM image showing the availability of small nano -sized grains of the $Al_3Mg_2$ phase adjacent to the $Al_{12}Mg_{17}$ [45]*

## 7. Conclusions

This research article describes the general trends and advancements in friction stir welding of aluminium and magnesium and their alloys. Despite the progress in Al-Mg dissimilar FSW technology over the last 20 years, critical elements such as microstructural stability, tool design, welding parameters and welding of novel alloys and metals still require much more investigation. Many areas of these elements are either untouched or inadequately focused.

This article uses a binary phase diagram to explain the basic science during friction stir welding of Al-Mg, taking into account the insufficient solubility of both metals. The next significant roadblock in producing brittle and harmful IMCs has been addressed by several contradictory ideas that explain it. The emergence of brittle IMCs is unquestionably a watershed moment in the evolution of dissimilar metal welding. The process of controlling the IMCs in dissimilar welding and techniques to avoid their creation has not been adequately pursued. Most of the research to date focuses on the genesis and dispersion of these IMCs; this area requires much more investigation to control the formation of IMCs to obtain the best welding joints.

Many research articles highlighted in this paper advocated that tool design, geometry, and positioning play an essential role in forming the defect-free weld. Most suggested using aluminium on the advancing side and magnesium on the retreating side to get type 3 interfaces during FSW of dissimilar Al-Mg welding. However, they are not clear about the exact best positions of the base materials in lap or butt welds; hence, this problem needs to be focused on in the upcoming research.

Finally, this article summarizes the latest advancements and developments in dissimilar FSW of Al-Mg. Furthermore, the recommendations given here should not be regarded as hard and fast laws but rather as general principles that might be applied to future events.

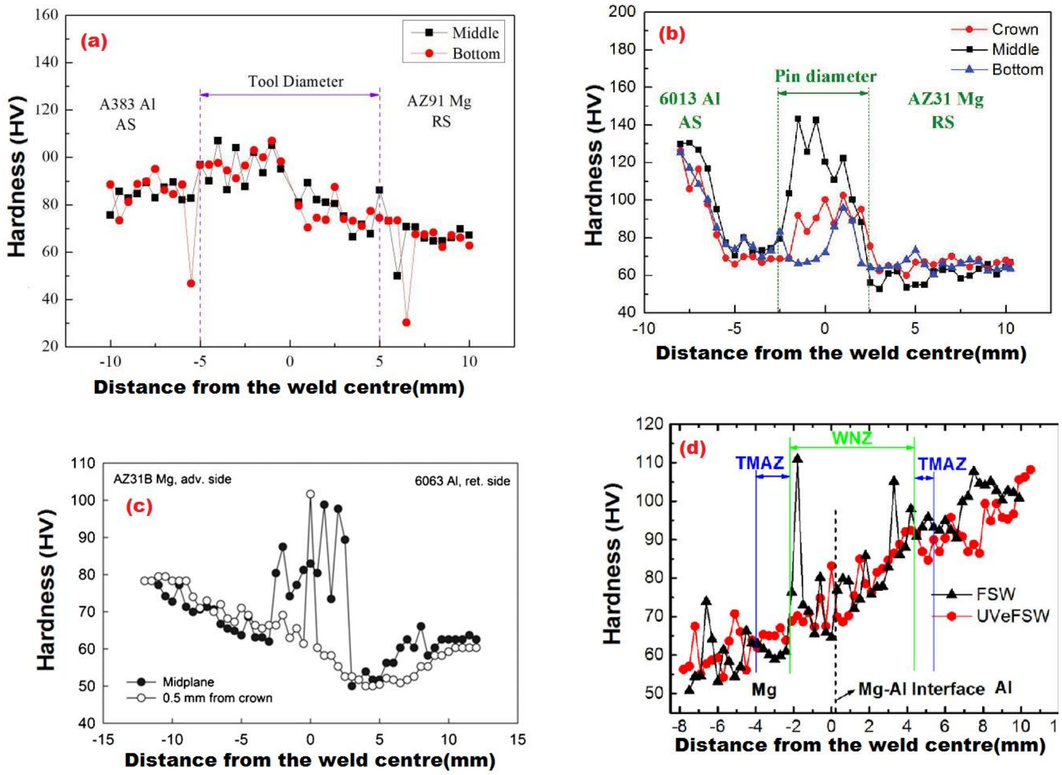


*Figure 6:Distribution in hardness level in FSW of Al-Mg:(a)Al-A383 & Mg-AZ91[53];(b)Al-6013 & Mg-AZ31[31];(c)Al-6063&Mg-AZ31B[54];(d)AA 6061-T4 & Mg-AZ31B[55]*

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