Mechanical Behavior of the Aluminum Alloys during Friction stir welding process: An overview

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Abstract. Aluminum now a days extensively used in many sector due to its compatibility and adaptability of the material for different grades. As It has been describe in the paper about various factor affecting FSW during operation like mechanical testing(by Shoulder, tool pin profile, tool rotation, welding speed) mechanical properties(Hardness, strength, fatigue), pre and post weld heat treated zone analysis (TMAZ, HAZ, SZ, NZ). Although many researchers vying to improve properties of the welded joint by many technique such as Bobbin tool, cold spraying, shot peening etc. we entails best possible chronological order to establish the right way of outcome and corroborate this theory for future references

Key words:- FSW , aluminium alloys, Hardness, tensile strength, fatigue ,Base metal

1. Introduction
Aluminum use in present era has been extensively plump up. Various sector influenced with the innate characteristics of aluminum and explicitly emphasizing on improving mechanical properties of pertinent alloys. Now sundries of aluminum alloys used in industries like defense sector, ship building, aerospace etc. Aluminum metric composite (Al+ceramic particles), Al alloy 7075, AA2024 alloys, Al-Li alloys, Al-mg-Sc alloys are examples of currently used material compounds grossly in myriad sectors. Good specific stiffness, strength to weight ratio, high toughness, and corrosion resistance is being some of the properties which envisage in aluminum alloys.

FSW is prominent technique used immensely for aluminum alloys joining. During joining precipitation hardening in weld area causes some ripple effect on metal properties as stated by literature [2, 3, 7]. Sharma et al[29] finds rotational speed of tool (Tr) and welding speed(Ws) maneuvering somewhat influenced the FSW joints mechanical properties (e.g increasing Tr and decreasing Ws improves strength of AA 7039 alloy), whereas Hao et al[30] research shows reduction in UTS value by increasing Tr & Ws of Al Mg Er joint [28]. Thermal disturbance of Al 7075 T651 with modeling evaluated by Zhang et al under FSW [33]. In AA2024 section higher fraction of grain boundary and brittle intermetallic phases formation improved hardness in FSW joints HAZ side reported. O & T6 tempering on Aluminium Alloys 6061-T6 rendered the ups and down in hardness value due to high welding speed along with enhancement of strength property [48]. Akbari et al [56] and Lee et al[57] observed that by inserting stirring pin with distant surface in base metal side become defect free of Al-Cu joint in FSW [55].

Bobbin tool (Bt) method used now a days for double sided FSW with alternative tool design[43]. In mechanical testing microstructure can be analyze by the exit hole site. Material flow during joining can be measure by the stop action method [38], as reported by the mironov et al this technique helps him to observed texture evolution in grain structure[37,39]. Material flow affected by the Tr speed and pin profile as reported by Ipekoglu & Cam [48,49]. Shot peening [70] or laser peening techniques in FSW sounds improved mechanical properties. In 6063-T5 alloys [71] et al reported abnormal grain growth (AGG) which degrade tensile strength and
hardness after heat treated (i.e. at 530°C/1hr followed by quenching and ageing at 175°C for 17hr) ingot underwent to FSW process [69]. Cold spraying (Cs) technique followed powder deposition method characterized by low temperature and high velocity particle [75, 76], hence it helps to alleviate oxidation, high speed particles speed up by a gas which flow incessantly and influence the substrate and ensued compressive residual stress on the surface by enhancing the fatigue performance alike shot peening effect (Spe) [74, 77, 78].

During mechanical testing of FSW assisted aluminum alloys various defects visible (e.g. cold flake, hardening cracks & voids, residual stresses, kissing bond). Hence various alternative method applied to eradicate these flaws. This paper designed in the wake of enhancement of the analysis for the impact of post welding treatments and changes in microstructure at the joining site (e.g. TMAZ, SZ, NZ, HAZ). This paper comprises the cause and effect of various methods while applying FSW so content of this paper will help the researchers for meticulously improve their outcome.

2. Factors affecting mechanical testing

2.1 Shoulder force

Shoulder in the FSW mechanism is being used to influence tool pin plunge depth into specimen [24, 26], Zhao et al. improves peak weld temperature [6], besides force applied by shoulder assist to weld tool rotation rate [27], increases micro hardness in weld nugget zone. Geometrical significance of shoulder may be ascribed by its diameter. Zhao et al in lieu of investigating the defects and tensile behavior of 6013 aluminum alloys in T joints under FSW observed that flowability of weld pool improved by increase in shoulder diameter vis a vis volume of heat input. Frictional contact between base metal surface (i.e. Ti-6Al-4V plates) and shoulder during investigating the rotation rate effect on Ti-6Al-4V alloys during FSW by microstructure and texture evolution by S.Yoon et al [85] observed basin shaped stir zone at the weld joints centre has been broadened.

As per F.X. Muthu et al. [34] observed that interfaces of shoulder and pin work pieces conspicuously shows heat generation in about 80:20 ratio respectively during investigating tensile and microhardness of Al-Cu joints accompanied with material flow with taking WPP, PTP and TTP pin profiles under microstructural characterization. Muthukumaran S et al. [35] & Krishnan K [36] et al reported that axial force support to the flow driven by the shoulder transfer bulk amount of material against the advancing which ultimately forms the onion rings.

2.2 Rotational rate of tool

Tool rotation is stemmed out with two concurrent application first one its speed and second one is its traverse speed. Increase in rotational speed of tool ensued mitigation of initial axial force with time improvement [24], increment of peak temperature [69], compatible decrement of spacing between the material bands [87]. M Jayaraman et al observed that beyond 1000 rpm tunnel defect appeared on the retreating side of A356 aluminium alloys under FSW. During Investigating the rotation rate effect on Ti-6Al-4V alloys during FSW by microstructure and texture evolution by S.Yoon et al [85] observed reduction in tool rotation speed resulted increment in area fraction of the equiaxed structure beside equiaxed α grain size subsequently unaffected by rotational speed. Zhang et al [28] reported that during increasing the rotation rate from 350rpm to 950 rpm, heat input vigorously improve which lead to robust strengthening effect of the natural ageing meanwhile ratio of tool rotation speed to tool traveling speed taken as the measuring criteria of welding heat input [48]. Mishra R S et al observed heat input in stir zone...
increases with rotational speed due to higher frictional heat which ensued in term of intense blending and stirring of material [25].

2.3 Influence of Pin profile
Tool pin geometry affects material flow [82]. Rotating pin action held responsible for mitigating the kissing bond defects during welding [5] while on the other side unstable pin depth causes for the occurrence of welding flashes. F.X.Muthu et al [34] observed during investigating tensile and microhardness of Al-Cu joints accompanied with material flow stated about flow dominance by the pin profile resulted in the material interlocking increment. Guerra et al [52] reported the material transportation methods with flushing out scrap from the advancing side of the pin into a region of material that rotates and advances with the pin.

H.I Dawood et al [81] observed during investigating the microstructures and mechanical behavior of 6061 aluminium alloys for measuring the effect of unchanged shoulder and small tool pin profiles concluded by observing pulsating stirring process in the material flow due to its first faces by the pin profile, gradual increment during calculating density at distinct joints ,& calculated density and lattice parameter of the grain structure can influence the strain hardening nature associated with tool pin profile during deformation. C.S Wu [37] examined the material flow , mechanical properties of AA 2024-T3 friction stir welded joint improved by ultrasonic vibration enable FSW for knowing the precipitate morphology by stop action method in the exit hole vicinity concluded the reduction in HAB fraction from 80.9% to 35.6 % due to the deformation induced by the pin in welding.

Jata.K.V et al [63] & Fonda .R.W et al [64] reported that stirring effect by the pin leads to dynamic recrystallization of the material as well as grain refinement in various aluminium alloys , which ultimately resulted due to frictional heating and plastic deformation simultaneous operation in FSW

2.4 Effect of welding speed
Fei zhang et al[28] examine the effect of welding parameters on mechanical an microstructural properties of super high strength Al-Zn-Mg-Cu aluminium alloy by joining it FSW found steep increase(about 96%) in elongation at 50mm/min welding speed. For enhancing the productivity and high strength welding Sergey et al[88] propounded an optimization of FSW 6061-T6 aluminium alloy in relation with processed microstructure properties post weld aging and stated that small cooling cycle become reason of grain growth suppression which de facto affected by increasing Ws and impressive refining of structure. M Jayaraman et al [24] observes For high tensile strength during very fine eutectic Si particle uniform distribution formation in Al matrix with no defects in SZ at Ws 75mm/min reported. While coarse Si particles & band structure in SZ reported at Ws 22 mm/min with joint strength reduction. Over the retreating side of Si particles & SZ channel defect observed at 40 mm/min.

3. Influence of mechanical properties in FSW
3.1 Hardness
Post welding hardness of weld joints varies as par to their heat treated zones Dinaharan et al [14] recorded maximum hardness as shown in fig. 1 in welded joints due to ZrB₂ particles volume increased. meanwhile the grain size of Aluminum in the weld zone may be mitigate by dynamic recrystallizaion. During analyzing the high temperature plastic behavior of aluminium alloys AA 5083-H11 and AA6082-T6 by performing mechanical characterization under varying loads and temperature by
Rodrigues et al [42] reported that AA5083 enlighten strong Portevin-Le-Chatelier effect and staged hardening with plastic deformation, flow stresses increases with load.

![Graph showing microhardness vs ZrB2 content](image)

Fig.1 illustrates comparative increase in hardness after ZrB$_2$ infusion in specimen AA6061 [14]

Besides ascertaining the effect of rotation and linear of the tool attributed the effect of welding heat input and post weld aging time mechanical characterization of AA 7075 & AA 5086 dissimilar friction stir welded plate Hamed et al[48] observed With heat sink arrangement minimum hardness of AA5086 side increased but the minimum hardness of AA7075 side decreased in as weld samples compare with the joints without sink. However Liu et al[51] state that the precipitate distribution, dislocation density, grain size and solid solution shophistically wielded changes in age hardenable and non age hardenable in FSW.

For enhancing the productivity and high strength welding Sergey et al[88] propounded an optimization of FSW 6061-T6 aluminium alloy in relation with processed microstructure properties post weld aging and resulted heavily dense uniformly spread in grains dispersoids. He found coarse Al(Fe,Mn) Si intermetallics. Transverse weld tensile plots showed portevin-Le Chatelier(PL) effect due to dynamic strain aging in plastic zone. This dynamic strain ageing, which is associated with the pinning and release of dislocations by diffusing solutes during plastic deformation, as shown in figure 2 was observed and reported in several solution strengthened alloy systems [88]. Its indicate high diffusivity of Mg atoms for vacancies yielded during plastic deformation. Serration have decreased in last stages of plastic flow observed after necking process.

TMAZ hardness decreases from the surfaces to the centre of the material due to distinct cooling rate & stir zone hardness improves as well.[15,24,28,33-34]. Huang et al [44] reported lean deformation at site of HAZ which causes higher microhardness than TMAZ during investigate the self support FSW effect on microhardness of 6082-T6 aluminium alloy, although he ensued Low micro hardness happen to be ubiquitous due to GP zones and overaged precipitates formation.
Surge in hardness reported in stir zone due to increase in rotational speed [72], precipitate dissolution into the matrix [87]. Fine equiaxed grain structure within NZ with grain size (2-7μm) & strain hardening [61] observed due to high temperature and extensive plastic deformation [67]. Loss in work hardening effect & pre exist dislocation reduction may be the reason for softness of NZ during FSW samples [62]. Decrease in hardness over stir zone obtain by recrystallization by Babu et al [61] during study of AlMg5-Al2O3 nano composites and their characterization under friction stir weld. He also reported Sample shows a reduction in yield strength & UTS in weld nugget compared to BM. Longitudinal specimens of AlMg5 Um weld displayed high strength and ductility than BM. When ultra vibration enable FSW applied than conventional FSW observes low micro hardness on the advancing side than that on the retreating side in AA 2024-T3 alloy [37]. High rotation speed and low feed rate results in wider softening region in low hardness. Subsequently a significant reduction of width reported when F/S ratio value kept high [90].

3.2 Strength
During the tension test various properties undergoes in consideration such as yield strength (YS), ultimate tensile strength (UTS), ductility. Many authors have evaluated UTS, percentage of elongation for alloys and based on that they certain with the fatigue behavior of material in practice and vying to further strengthen the material property. FSW has reckoned on the parameters in heat treated zone for infusing vigorous material properties during joining process went underway. As Wenya Li [7] et al observed while examining the effect of the backplate diffusivity from low diffusivity of granite to high diffusivity Cu in order to reveal mechanical properties of prior during FSW from figure 3 that 3(a) demonstrate smaller fracture strain of joints than that of base metal.

As because lower plasticity of granite and Cu backplate than base metal there yield strength too reported comparatively lower. 3b&c backplate diffusivity UTS increases and after certain point drastically decreases as void defect exist at nugget zone of advance side. Zhao et al [4] while investigating the defects and tensile behavior of 6013 aluminium alloys in T joints under FSW observed found that for T lap joint UTS alongwith skin increases with traverse speed. One of its specimen has highest UTS of 238 MPa equivalent to 70% that of BM, however UTS alongside the stringer decreases with increases traverse speed.
Figure 3. Shows EBSD maps of (a) Base metal yield strength (b) due to voids changes in UTS regarding to the granite and (c) steel backplate [7].

During measuring the effect of the AA7005/10 vol% Al₂O₃ by the means of friction stir welding A Morri et al [15] observed 20% decrease of the proof and tensile strength and reduction of the elongation to failure in sample W7A10A and resulted joint efficiency of about 80% respect to UTS. While evaluating the effect of the initial surface oxide film of AA2219-T62 alloy under FSW and accessing the Joint line remnant during operation T. Lina et al [60] reported black particle of JLR in continuous strip distribution with size 10 μm as exhibit it figure 4. one specimen TS and elongation of BM is 76% & 71% due to the removal of oxide from the plate edges before welding.

During tension test void observed in nugget zone [84], meanwhile in aluminium alloy 1050 created by ultrafined grained reported higher yield strength and tensile strength in base metal than nugget zone[91]. In FSW operation the Zhang et al [28] attributed Mechanical heterogeneity which induced low UTS while thick second phase dense particles and coarsening of the strengthening precipitates presents in NZ and HAZ or TMAZ respectively. D Rao et al [1] in order to predicting the mechanical behavior of aluminium alloy 5083 in between advance side and retreating side observed that at base metal fracture strain was at 16 % higher fracture results in lieu of reduction of YS and increase in strain hardening property due to recovery and recrystallization on specimen.

3.3 Fatigue behavior post FSW
The failure mechanisms typical of particles reinforced aluminium-based composites are: (i) cracking of large reinforcing particles, (ii) interfacial decohesion at the particle–matrix interface, resulting in nucleation of voids, and (iii) growth and coalescence of voids in the matrix [16-23]. In various test undergoing for calculated by researchers attributed distinct phenomena attained near welding fusion arena. D Rao et al [1] in order to predicting the mechanical behavior of aluminium alloy 5083 in between advance side and retreating side and Zhao et al while investigating the defects and tensile behavior of 6013 aluminium alloys in T joints under FSW observed fatigue failure in HAZ at the RS under tensile
loading & near RS of weld line as absence of tunnel defect but presence of kissing bond defect as displays in figure 5(a) & (b) near RS respectively.

![Image](image_url)

Figure 4. Microstructure displays by arrows in distinct angles joint line remnant in black[84]

During the analysis various defects envisages in picture like oxide array remnant(Kissing bond/induced crack [4] & and tunnel defect which is responsible for area deduction along the stringer[5]. During analyzing the backplate diffusivity on granite and Cu plate under FSW Wenya Li et al [14] reported in figure 5 under granite backplate joints shows a little river like pattern covered with shallow dimples and tearing edges in high magnification different layered ledges and grooves appeared, Which indicate it has quasi cleavage and dimples sort of fracture characteristic. Random sprawled fine microscopic cracks and myriad voids of varying sizes and shapes observed. He also observes h phase particle (Al2Cu).

During analyzing the backplate diffusivity on granite and Cu plate under FSW Wenya Li et al [14] reported that In the wake of fracture surface observation of AA6061/5 wt% ZrB2 , they observes nexus of dimples shown in figure 6 those are smaller in size than matrix alloy. ZrB2 particles refined the grain size of alloy and decrease the ductility resulted in small dimples and its volume fraction improves the fracture flatness as well as ZrB2 aluminum matrix composites exhibit broken clusters and particles fragmentation which causes difference in dimple sizes. For investigating mechanical and fracture properties over AA7005/10 vol% Al2O3 composite b. Minak et al [15] concluded high total strain value range which may be proliferate fatigue live ratio1:30 at Max and 1:10 min.under low cycle fatigue testing whereas Manson Coffin model assist to interpolate prescribed data as given in literature [17-19].

At central zone low concentration of dimples and flat striated fracture with voids appeared near bottom zone[28]. Meanwhile large voids accompanied with little dimples and teared ridges with matrix decohesion of particle appeared during the fatigue measurement base metal reported cleavage steps with large dimples with residual phases and tearing edges which are apparently found in trans granular dimples. Large quantity of 2nd phase particles diffused and generate tiny ans shallow dimples. By energy spectrum analysis , the thick second phase particles observed were identified as the quaternary T (AlZnMgCu) phase with a broad composition range [31,32].
Figure 5. Microstructure illustrate defects of 4 different samples of 6013 aluminium alloys (a) Kissing bond in AS (b) Kissing Bond in RS [4,5]

C.S Wu et al [37] examined the material flow, mechanical properties of AA 2024-T3 friction stir welded joint improved by ultrasonic vibration enable FSW for knowing the precipitate morphology by stop action method in the exit hole vicinity observed in fatigue that 3D shaped
particles at the bottom of the dimples at UVeFSW joint and found desquamation of precipitate phases on the tearing edges around the dimple due to micropores. Fracture in between AA6061-T6 & AA6082-T6 joint occurred near TMAZ and HAZ interfaces [41], while in AA 2024-T3 alloys at high welding speeds fatigue obtained near un notched base metal and FSW joint by Moreira et al and Biallas et al [52]. As per ASTM E647 [91] crack Propagates in AA2198 Al-Li alloys joints, however a reduction in crack growth reported due to recrystallization and residual stresses.

Fig 6 (a) large size dimples due to plastic flow before failure (b) AA6061/5 wt% ZrB2 AMC Smaller size of dimples than matric alloy (c) fine dimples on welded matrix due to fine grains in weld zone & (d) AA6061/5% ZrB2 AMC enlighten particles fragmentation and clusters torn apart partially[14]

Elongated tear ridges and deep dimples of JLR particles analyzed by Lin et al [60] and resulted locate Scalloping in advanced side as this structure appeared due to original joint faying surface during FSW. Bavazid et al reported fine dimples which ascertain high value for ductility on cyclic solution treatment [23] surges from coarse precipitates and determines average grain sizes of the base metal by line intercepted method. Many authors compared CST with conventional solution treatment and performed mechanical properties on AA 6063 and AA7075 aluminum alloys [24,25].

4. Post welding impact of heat treated welding zone
4.1 Thermo-mechanically affected zones
As illustrating all respective fusion zone in figure 7. The thermo-mechanically affected zones (TMAZ) posits to sides of stir zones, strain hardening and temperature values plunge in this region. At TMAZ dynamic recovery [28] and recrystallization [7, 44, 67] found near retreating side of advance side of the weld zone. During analyzing the backplate diffusivity on granite and Cu plate under FSW Wenya Li et al [7] reported sharp NZ/TMAZ interface appeared due to irregular material deformation with micro crack formed in weak zone of it, while sharp entity of interface depicts existence on the advance side as UTS of the weld under granite plate is lower than steel back plate. With using ultrasonic fatigue testing method to investigate the VCHF strength of the FSW joints in AA7075-T6 alloys Chao et al [67] reported
more flattened and shorter crack length in NZ than TMAZ due to fine and equiaxed recrystallised grains besides large VHCF range for test. Mg$_2$Si particle appeared in TMAZ due to plastic deformation. According to [48] in TMAZ strengthening precipitates of size (70nm to 220 nm diameter larger than base metal) intensely counter coarsening as well as reduction in density. During employing heat sink diffusion of solute atoms from aluminium matrix to precipitate becomes lower in the TMAZ.

![Figure 7 Showing various fusion zone in friction stir welding [67]](image)

During the analysis of AA6061/ZrB$_2$ in situ cast composites by Dinaharana et al [14] TMAZ unravel the ZrB$_2$ particles aligned vertically. He observed high dislocation density and sub grain structure in TMAZ region in the meantime microhardness reported in TMAZ due to strain hardening, reprecipitation and GP zones formation after natural aging. Huang et al observed dissolution of precipitates which is explicitly depends upon the thermal cycle in TMAZ on the other hand Sato et al [45] stated that because of the peak temperature is lower than the solvus temperature of 6082-T6 aluminium alloys large amount of uniform and second phase particle are distributed in the TMAZ.

4.2 Heat affected zone
This zone prone to thermal cycle without deformation during solid state welding. Zone is attributed to the lower temperature than those in TMAZ. In fact, in age hardened aluminum alloys poor mechanical properties exhibited in this zone. D Rao et al [1] in order to predicting the mechanical behavior of aluminium alloy 5083 in between advance side and retreating side observed decreased material strength from the base metal to the HAZ whereas ductility increased at RS At HAZ strength dropped and stabilized in the SZ. Fei Zhang et al [28] found in HAZ region intragranular and grain boundary precipitates have coarsened and density decreased in comparison to the base metal. Mg$_2$Si phase dissolution truncated dendritic structure arms. F.X.Muthu et al [34] observed coarser grains in HAZ though these grains are becomes leeser in size than WPP pin (i.e as it illustrate at aluminum side TMAZ region grains become lineate towards the stir zone) during investigating tensile and microhardness of Al-Cu joints accompanied with material flow with taking WPP,PTP and TTP pin profiles under microstructural characterization.
4.3 Nugget zone

With using ultrasonic fatigue testing method to investigate the VCHF strength of the FSW joints in AA7075-T6 alloys Chao et al [67] observed Fe rich particles(3 to 5μm diameter) and Mg2Si particles (6 to 10μm)in dynamic recrystallization during severe plastic deformation and frictional heating in NZ. Rather than crack initiation begin from particle self cracking it’s got to started from debonding between the particle and the matrix. However in NZ fatigue crack initiation ascribe to the precipitate free zone in grain boundaries of aluminum matrix[68]. Many authors have been resulted two stirred structure first one is intercalation swirls[58] and vortex like patterns[59].Huang et al arrangement of Threaded stir pin assist material is forced down into the weld by multiple rotational and welding speed[46].author segmented of the weld nugget zone in upper and lower sides of weld joint observes the distinct role of stir pin and shoulder pattern opt by other authors[47] Lipinsk et al [91] concluded that the grain elongation factor (dmax/d2) value is 1.36 approx. alike equiaxed grains

Usually fine equiaxed grains achieved by dynamic recrystallization from SPD and high frictional heating[93-94]. Fei Zhang et al [28] examine the effect of welding parameters on mechanical an microstructural properties of super high strength Al-Zn-Mg-Cu aluminium alloy by joining it FSW At 50mm/min weld speed second phase particles founds unchanged. Cooling cycle in welding thermal cycle exhibit fine precipitates within grains and their boundaries. Second phase particle size reduced after tool rotation increased 350 to 950 rpm. During analyzing the backplate diffusivity on granite and Cu plate under FSW WenyaLi et al [7] reported complete recrystallization which comprises fine equiaxed grains. He found lower hardness in NZ than the BM due to mobile dislocations at short intervals in region. Hardness increases alongwith decrease in backplate diffusivity.

4.4 Stir Zone

F.X.Muthu et al [34] during investigating tensile and microhardness of Al-Cu joints accompanied with material flow found Cu particle is excavated from the AS and mixed in the stir zone due to taper pin profiling. Alternate stacking of Al and cu is being reported majority of Al particles. Recovery and recrystallization in the weld zone reduces strength and dislocation density which assist to yield fine grain size as given by other researchers [2,3], hence the gradient of yield strength at the AS attain more than twice the RS.

C.S Wu et al [37] examined the material flow, mechanical properties of AA 2024-T3 friction stir welded joint improved by ultrasonic vibration enable FSW Expansion in SZ and deformation zone of AA204-T3 in duration of UVeFSW joint corresponding to surge in material transport and flow due to the softening of workpiece ahead of the tool pin to ultrasonic vibration densely accumulated precipitates of coarse and fine shape in FSW and UVeFSW respectively spread across the stir zone. While area fraction of the precipitation in FSW(4.67%) and UVeFSW (4.23%) joints are alike in the coarse but fragmented in fine particles in SZ.

Hamed et al [48] found Equiaxed grains with length forms in stir zone of AA5086 (87±0.7) μm with coarse & AA7075 (75±0.5) μm with less coarse than obtained due to dynamic recrystallization. However grain size of stir zone substantiate the dependence its changes over heat input and strain imposed by plastic deformation[50]. Investigating the rotation rate effect on Ti-6Al-4V alloys during friction stir welding by microstructure and texture evolution by S.Yoon et al [85] observed that high temperature β phase texture in [0001] direction appeared before
phase transformation. High tool rotation rate cause for the increment in β phase after surge in temperature FSW. Dynamic and static recrystallization build plastically deformed equiaxed α grains as low peak temperature attained. Under different heat input and post weld heat treatment on stir zone hardness for FSW 204-T3 aluminium alloys by Chen Yu et al[72] Reported granule shaped S phase and coarse Ω phases in stir zone appeared after short time of higher temperature. Many authors found prominent effect of S phase for hindering anomalous grain growth in Al matrix by pinning dislocation [5, 38, and 41]. High angle grain boundaries in SZ with misorientation angle greater than 15° of as welded and coated joints shared 57.4% and 67.5% of the total grain boundary length.

4.5 Onion ring formation

Fig(a) D Rao et al [1] in order to predicting the mechanical behavior of aluminium alloy 5083 in between advance side and retreating side as shown in figure 8(a) observed Distances between the rings varied during progression towards centre to periphery. Ring clearly visible at AS close to SZ while blurred at RS. Huang et al [44] (fig 8b) during investigate the self support FSW effect on microhardness of 6082-T6 aluminium alloy observed single OR near weld nugget in FSW and replaced by series of OR pile up vertically through the AS thick side. While evaluating the effect of the initial surface oxide film of AA2219-T6 alloy under FSW and accessing the Joint line remnant during operation T.Lina et al [60] OR observed at central NZ and TMAZ (fig 8c) around CNZ. Particles consist 64 at% O and 35 at% Al. Babu et al [61] investigate over AlMg3-Al2O3 nano composite microstructural characterization of friction stir welding articulated that onion ring pattern results from the interaction between the material flow driven by the rotating pin and the shoulder-driven flow. Pseudo elliptical shaped OR in central ST direction of the weld joint with about 500 micron m spaced in between.

Fig(b)
5. Calculative Analysis of Friction stir welding

Apparent the hardness in the post weld structure assist to measure grain size by having Hall Petch relationship [13] as given in equation 1 below

\[ H_v = H_0 + K_H d^{-1/2} \]  

Eq. 1

Where \( H_0 \) & \( K_H \) are the constants with \( d \) as a grain size.

\[ Q = \delta Q_{\text{sticking}} + (1-\delta)Q_{\text{sliding}} \]  \hspace{1cm} Eq. 2

Here \( \delta \) is contact state variable. On the other hand tool probe side surface heat in sticking and sliding \( (Q_{ps1} \text{ & } Q_{ps2}) \) may be measured by below equation 3 and equation 4

\[ Q_{ps1} = \theta \tau \Omega \left( \frac{d}{2} \right)^2 H \]  \hspace{1cm} Eq. 3

\[ Q_{ps2} = \theta \mu \phi \left( \frac{d}{2} \right)^2 H \]  \hspace{1cm} Eq. 4

Here \( \theta \) is probe and technological hole between contact angles. Weld work piece shear stress is \( \tau \), angular rotation speed of tool is \( \omega \), probe tip diameter is \( d \), coefficient of friction between weld piece and tool is \( \mu \), pressure produce in between contact of weld piece and tool is \( p \), and addition of probe side height and shoulder depth is \( H \) [43]
During characterization of nano composites of aluminium alloys N. Babu used Critical radius for the nucleation of recrystallized grains $R_c$ according to Gibbs –Thomson relationship is given as by equation 5 [65]

$$R_c = \frac{A_{gb}}{P_{gb} - PP_Z}$$  \hspace{1cm} Eq. 5

A smaller size of RC for a given material suggests a higher tendency for recrystallization and the values of $R_c$ depends on grain boundary energy ($Y_{gb}$), stored deformation energy ($P_{gb}$) and ($P_Z$) is referred as the Zener-drag has been shown by equation 6 [61]

$$P_Z = \frac{3f_{gb}}{2r}$$  \hspace{1cm} Eq. 6

for a high volume fraction ($f$) and smaller radius ($r$) of reinforcements for the AA5083 welds The pressure parameter, which was calculated using the equation 7 mention below reflects the influence of the axial load ($F_z$) and tool parameters ($D_s$ and $D_p$) on welding results [42]

$$P = \frac{F_z}{\frac{D_s^2}{2} - D_p^2}$$  \hspace{1cm} Eq. 7

For analyse the cold spraying effect on optimized friction stir welding of AA2024-T3 joint Lia et al [74] used following equation 8 & equation 9 given by Genevois et al [80] for calculate relative fraction of GPB and presence of S phase.

$$f_{GBP} = \frac{S_A}{S_{gb}}$$  \hspace{1cm} Eq. 8

$$f_S = 1 - \frac{S_B}{S_{bo}}$$  \hspace{1cm} Eq. 9

Here ‘S’ and ‘O’ stands for peak area and base metal respectively. He observes GPB as the main precipitant for hardness meanwhile S phase cast as the small size hardening agent.

Under different heat input and post weld heat treatment on stir zone hardness for FSW 204-T3 aluminium alloys by Chen Yu et al[p34] utilizes Orowan-Ashby equation [95,96 ] to evaluate mechanical properties or sometimes aluminum alloys hardness [97] as shown in equation 10

$$\Delta \sigma = \frac{0.136b}{\lambda} r^2 \ln \frac{r}{b}$$  \hspace{1cm} Eq. 10

Here interparticle spacing is denoted by $\lambda$, particle radius by $r$, and $b$ is the Burger vector ($2.84 \times 10^{-10}$ m for Al).

Coffin and Manson ascribed fatigue life due to plastic strain amplitude by stress and strains analysis in notched regions for ductile metals band of points may be approximated by log plot of the fatigue life to steady plastic strain amplitude (SAE 1968) hence following equations are

$$\frac{\Delta \epsilon_p}{2} = \epsilon_f (2N)^c$$  \hspace{1cm} Eq. 11

$$\frac{\Delta \epsilon_p E}{2} = \sigma_0 = \sigma_f (2N)^b$$  \hspace{1cm} Eq. 12
\[ \frac{\Delta \varepsilon}{2} = \varepsilon_f' (2N_f)^c + \frac{\sigma_f}{E} (2N_f)^b \quad \text{Eq. 13} \]

\[ \frac{\Delta \varepsilon}{2} = \varepsilon_f' (2N_f)^c + \frac{\sigma_f - \sigma_m}{E} (2N_f)^b \quad \text{Eq. 14} \]

Here plastic strain in equation 11 where \( \frac{\Delta \varepsilon}{2} \) is amplitude, \( \varepsilon_f' \) fatigue ductile component, \( c \) is fatigue ductile exponent, by monotonic tension test true fracture ductility, \( \varepsilon_f' \). \( \frac{\Delta \varepsilon}{2} \) is the elastic strain amplitude, \( \sigma_a \) stress amplitude, \( E \) modulus of elasticity, \( N_f \) fatigue strength coefficient (i.e stress intercepted at one load reversal), \( 2N_f \) the number of reversals to failure or twice the number of cycles, \( b \) is fatigue strength exponent or Basquin exponent, \( \sigma_m \) mean stress.

From the correlations between hardness and ultimate tensile strength (\( \sigma_t \)) that could be found in the literature the only one that is dedicated to aluminium is proposed by the Japanese Society of Materials Science (JSMS), equation 15 [98]

\[ \sigma_f = \frac{(HV - 21.9)}{0.242} (\text{MPa}) \quad \text{Eq. 15} \]

As per ASTM(2000) HV may be converted to HB by equation 16

\[ HB = \frac{HV + 2.9744}{1.2005} \quad \text{for } 40 \leq HB \leq 160 \quad \text{Eq. 16} \]

From the approximations for aluminium alloys presented in [98] the uniform materials method equation 17 and the medians method equation 18 are applied in this study:

\[ \frac{\Delta \varepsilon}{2} = 1.67 \frac{\sigma_f}{E} (2N_f)^{0.05} + 0.35 (2N_f)^{0.69} \quad \text{Eq. 17} \]

\[ \frac{\Delta \varepsilon}{2} = 1.9 \frac{\sigma_f}{E} (2N_f)^{0.11} + 0.28 (2N_f)^{0.66} \quad \text{Eq. 18} \]

6. Relevance of various parameters described in tables

We have reviewed friction SW mechanical Behavior; alongside that study we observed that various alloys undergo distinct chemical and mechanical treatment. Samples have distinct length, width and thickness where according to the tool rotational speed, their corresponding weld speed may vary. In the meantime how much axial force we applied exclusively rely on former parameter

Table No. 1 Exhibit distinct mechanical working and chemical treatment of various alloys

| Mechanical working                          | Material       | Polish & etching                      |
|---------------------------------------------|----------------|--------------------------------------|
| cold rolled H temper[1]                     | AA 5083        | 75-90s in barker’s reagent           |
| Melt in electrical furnace with graphite crucible[14] | AA6061T6       | 1g NaOH, 4g KMnO4                    |
| 465°C/1h, water quench, ageing 95°C/1h & 145°C/16h[15] | AA7005         | keller’s reagent’s                   |
| Sand casting[24] | A356 alloy | 5% hydrofluoric acid |
|-----------------|------------|---------------------|
| Conventional casting. 2 state homogenization (400°C/4h+470°C/30h), hot extrusion (extrusion ratio 17.7), water quench-heat treat 470°C/3h-ageing 120°C/24h[28] | super high strength Al alloy | Keller's reagent's (1ml HF+1.5mL HCl+2.5mL HNO3+95mL H2O) |
| Artificial ageing at 180°[40] | AA6082 T6 & AA6061 T6 | HF reagent |
| Size cut by power hacksaw and grind[53] | AA2219-T87 | Keller's reagent |
| Material extrusion at 380°C with 75% reduction [88] | AA6061 | Keller's reagent/electropolishing in 25% nitric acid in methanol for EBSD & TEM |
| T6-solution heat treated followed to ageing and T6 for HT then temper[60] | AA2219-T62 | |
| Pure Cu annealed at about 650°C/1h, cooled in air[55] | AA1060 | 5mL H2O2+45mL NH4OH |
| Post weld HT 155 degree C/30h[103] | AA2050-T3 | Polishing up to 1/4 micron using OP-S solution and etching in 40mL tetrafluorooboric acid (HBF4) 760mL water with 0.2 A/cm² |
| Al & Cu sheets annealed at 350°C and 650°C[100] | | Al side of the welds was electro-etched by 10 ml HBF4 & 200 ml distilled water at a voltage of 26 V for 80 s and grain structure was revealed by using polarized light. Afterward, the copper side was etched with a solution of 5 g FeCl2 & 50 ml HCl & 100 ml H2O |
| Cold rolled sheets annealed at 300°C/2h, FSW joints aged 120°C/16.5h[101] | | Specimens were polished and then etched with a solution of 10 mL phosphoric acid and 90 mL water at 80°C |
| Post weld HT at 170°C/6h, water quench then 190°C/13h, and water quench[102] | AA 6056 | Keller's reagent |

6.1 Mechanical working and chemical treatment of various alloys (Table 1.)
Researchers used numerous mechanical working for processing in FSW. Cold rolled H temper performed under Barker reagent for etching & polishing operation [1]; Quenching & ageing process applied over
SHSAA under Keller’s reagent [28]; Artificial ageing done on AA6082 T6 & AA 6061 T6 plates with HF regents[40]. Researchers used some other mechanical working processes i.e casting, extrusion, rolling. Many researchers also used Heat treatment like tempering, annealing, quenching ageing process for refinement of weld material. Many experiments used NH4OH, HBF 4 , HNO3 sort of etching solution.

6.2 Dimensions of various samples (Table 2.)
Researchers maintain the specimen length range (80-1200)mm, width ranges in between(50-500)mm, and thickness of plate ranges between 2.5 mm to 10mm.

Table 2. Shows L*W*t dimensions of various samples

| Sample material | Specimen Length (mm) | Specimen width (mm) | Specimen thickness(mm) |
|-----------------|----------------------|---------------------|------------------------|
| AA7075-T651[67] | 1200                 | 500                 | 10                     |
| AA5083 H321[104]| 750                  | 100                 | 6                      |
| AA2024 T3[54]   | 600                  | 80                  | NA                     |
| AA2198[37]      | 500                  | 300                 | NA                     |
| AA 5083[1]      | 400                  | 120                 | 3                      |
| AA1060[55]      | 300                  | 100                 | 3                      |
| AA6061T913[43]  | 300                  | 200                 | 4                      |
| AA6063-T6[33]   | 300                  | 100                 | 3                      |
| AA2219-T87[53]  | 300                  | 150                 | 5                      |
| Ti-6Al-4V[85]   | 300                  | 35                  | 2                      |
| AA 6082-T6[44]  | 300                  | 100                 | 5                      |
| AA 6061[34]     | 210                  | 100                 | 4                      |
| 6013-T4[5]      | 210                  | 110                 | 2.5                    |
| AA 2024 T4[7]   | 200                  | 95                  | 3.175                  |
| 5A02[105]       | 200                  | 50                  | 3                      |
| 6056[102]       | 200                  | 80                  | 4                      |
| 2024-T3[74]     | 200                  | 100                 | 3.2                    |
Table No. 3 Illustrate various process welding parameter

| Material | Tool rotational speed (rpm) | Welding speed (mm/min) | Axial force (kN) |
|----------|-----------------------------|------------------------|-----------------|
| AA5083[1]| 1800                        | 1000                   | 9.5             |
| AA2024 T4[7]| 600                        | 200                    | NA              |
| AA6061 T6[14]| 1150                       | 50                     | 6               |
| AA7005[15]| 600                         | 300                    | 12              |
| AA6063 T6[33]| 1000                       | 550                    | 4.5             |
| AA6061[34]| 1750                        | 60                     | 7.5             |
| AA2198[37]| 600                         | 300                    | 8.5             |
| AA7075 T651[52]| 1500                       | 50                     | NA              |
| AA1100 H14[81]| 1075                       | 70                     | NA              |
| AA7024 T3[54]| 600                         | 80                     | NA              |
| AA6061 T913[43]| 940                         | 18                     | NA              |
AA7075-T651[67] 300 150 NA
AA1060[55] 1050 30 NA

6.3 Various process welding parameter (Table 3.)
Researchers maintain tool rotational speed from 300 rpm to 1800 rpm, welding speed from 18 mm/min to 1000 mm/min along with this some researchers used axial force ranges from 6kN to 12kN.

7. Conclusions:
This article elucidates the summary of the results and experimentation conducted of the papers. We observes that during mechanical testing we have to kept close watch over parameters like shoulder force, rotational rate of tool, pin profile, welding speed. We have concluded that for ensuring better welding result, we should emphasize on hardness & strength kind of properties. We observers crucial fatigue behavior near HAZ,NZ, TMAZ, whereas we can generalize that during material flow onion ring formed across welding region. It will authorize to reader in further strengthen their cumulative knowledge in regarding the friction stir welding and commensurately applied adequate methodology for the right approach in future.

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