Numerical and experimental investigation of defects formation during friction stir processing on AZ91

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Abstract

The heat generated during friction stir processing greatly affects defects formation in the processed zone of workpieces. In this paper, numerical modeling of this process is performed to determine the influence of tool rotational and traverse speeds and hence their ratio on the thermal distribution attained during the process. The aim is to produce defect-free processed samples by selecting adequate tool speeds. The mechanisms of defects formation depending on the peak temperature are also investigated. Experiments to verify the simulation results were conducted with the same process parameters. Several traverse speeds of 20, 40, 60, and 80 mm/min and rotational speeds of 700, 1000, 1200, and 2000 rpm were used during modeling and conducting the experiments. From the numerical and experimental results, it was found that; the high-speed processing conditions (low-generated heat) can produce defects such as tunnels and grooves, and the low-speed processing conditions (high-generated heat) can cause defects such as flashes. The experimental results show that during friction stir processing with the rotational speed of 1200 rpm and the traverse speed of 60 mm/min (speed ratio of 20), no macro defects in the processed zone were observed. According to the numerical results, the peak temperature during friction stir processing with these speeds was 475 °C. At this temperature, the material softened, the structure finely equiaxed and no large scale melting zone appeared in the processed zone. The developed model can be useful to investigate the occurrence of defects associated with different tool rotational and traverse speeds.

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Graphic abstract

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1 Introduction

The high strength to weight ratio and considerable weight saving potential have increased the demand for magnesium alloys such as AZ91 (as the best castable alloy) in various industries [1–4]. Lower energy consumption and environmental considerations have also increased research attempts for improving the microstructure and hence the mechanical properties of these alloys. In spite of advantages, the unstable eutectic phases due to grain boundary sliding mechanism cause a reduction in the creep and tensile strength of AZ91 cast alloys [5]. Therefore, Mg alloys cannot be used in applications that need thermal stability up to about 200 °C. In this regard, the severe plastic deformation (SPD) methods have been employed for dissolution of these unstable phases, decreasing the casting defects, improving the microstructure and increasing mechanical properties [6–8]. During this process, dynamic recrystallization (DRX) causes a fine structure and equiaxed graining in the stirred zone. Several researchers have investigated the effect of friction stir processing (FSP) on lightweight structures such as Mg alloys and Al alloys. Raja et al. [9] concluded that the rough casting structure of AZ91 alloy refined slightly, the lattice eutectic network broke into pin-like particles, the defects eliminated, and the tensile strength and impact property increased. Lua et al. [10] mentioned that despite the breakdown of the

eutectic networks, the graining of Mg alloys was not finely homogenous and process defects appeared in the stirred zone (SZ).

Recently, some researchers investigated the influence of tool shape and process conditions on defect formation [11–13], microstructural, and mechanical properties [14–16]. Prevention of defects formation during FSP is very important to produce a quality workpiece. Shamsudeen et al. [17] demonstrated the influence of tool shape on microstructural properties and tensile strength of AA 5052 H32 aluminum alloy. Govindaraju et al. [18] studied the influence of FSP with several heat treatment conditions on the microstructural evolutions of AZ91. They reported coaxial graining and excellent strength after heat treatment. The literature review shows that pin geometry, and tool tilt are effective parameters on defect formation, but the variation of tool geometry is costly [19].

Innovative methods have recently been developed to modify the microstructure, improve the mechanical properties, and prevent the defects formation after FSP [20]. Stationary shoulder FSP (SSFSP) is a technique to improve the superplasticity of the friction stir processed workpieces. In this technique, the tool shoulder does not rotate and only the pin rotates. Therefore, during this process, the rotating pin generates heat and the shoulder provides only the required pressure for performing FSP [21]. This method causes a smooth surface, forms a linear heat input

profile in the thickness direction of the processed samples, decreases the peak temperature and heat-affected zone (HAZ) width, and consequently reduces the process defects. Another innovative method for improving the superplasticity properties could be using the dual rotational tool. In this technique, the shoulder and pin rotate at different speeds [22]. Non-rotating shoulder during SSFSP and optimized rotating speed of shoulder during dual rotational FSP avoid melting material at the interface of the shoulder and the workpiece, and reduce the thermal and fusion-related defects [23, 24]. In a similar research, Patel et al. [25] demonstrated the effect of SSFSP on microstructure modification grain refinement of Mg alloys. They reported that after SSFSP, with decreasing the process defects and improving the microstructure (compared to usual FSP), the hardness and ultimate tensile strength (UTS) increased by ~ 80% and 24% respectively compared to that of the base metal (BM).

In addition, hybrid FSP [26] with different cooling media (compressed air, water, ice, refrigerants) increases the cooling rate and improves the microstructure to produce ultrafine-grained structure and reduces the process defects. Recently, researchers [27] have reported that water-submerged FSP refines the structure and improves the superplasticity properties in Mg alloys. In a similar work, Heidarpour et al. [28] investigated the effect of cooling media on the microstructural evolution and tensile strength of AZ91. They observed that after FSP, the non-homogenous structure changed into equiaxed graining, the lattice secondary phases converted into small particles, the structure of submerged workpieces was more homogenous compared to that of processed workpieces which were not cooled, and the ductility of friction stir processed workpieces (with water cooling) reduced.

Although these innovative methods make a relative improvement in properties and significantly reduce defects, however, the high cost of implementing these methods has severely limited their use in industrial applications. Therefore, in recent years, to prevent the formation of process defects and increasing the mechanical properties, some researchers [29–32] studied the influence of process parameters (especially process speeds which are easily varied and can affect the amount of the heat generated) on microstructure and mechanical properties. Zhang et al. [33] observed that increasing the rotational speed to more than 1400 rpm caused the formation of voids in the SZ. Kim et al. [34], Ren et al. [35], and Moussawi et al. [36] studied the influence of rotational and traverse speeds on defects formation during FSP of aluminum alloys. In this regard, investigating the thermal aspects (peak temperature and thermal distribution) of FSP has attracted attention. FSP is a coupled physical and thermomechanical process and the

heat generated during this process is related to plastic deformation and frictional contact [37]. For explaining the importance of investigating the effect of temperature distribution on the quality of the part, it is to be noted that during FSP, the material should be softened, stirred, and subjected to necessary heat for DRX. However, a large scale or obvious liquid state should not be created in the processed zone. If FSP is carried out under inappropriate processing conditions, several macro and micro defects like grooves, tunnels, and flashes are produced due to insufficient material flow, excess, or insufficient heat input and inappropriate pressure. Thus, to produce a defect-free workpiece, it is necessary to use proper rotational and traverse speeds.

Arbegast and Hartley [38] presented an empirical relation (Eq. 1) between the peak temperature ($T_{\max}$), melting point (T_m), rotational speed (ω), and traverse speed (v) during FSP of Al alloys. In this relation, the constant $K = 0.65 - 0.75$, and the exponent $\alpha = 0.04 - 0.06$.

$$\frac{T_{\max}}{T_m} = K \left(\frac{\omega^2}{v \times 10^4} \right)^\alpha \quad (1)$$

Frigaard et al. [39] have given Eq. 2 to investigate the heat input per unit length:

$$Q = \frac{4\pi^2 \alpha \mu P \omega R^3}{3v} \quad (2)$$

ω : Rotational speed [rpm],
 v : traverse speed [mm/min],
 R : Tool shoulder radius [mm],
 α : Heat input efficiency,
 μ : Coefficient of friction,
 P : Pressure [N/mm²].

Chen and Kovacevic suggested the heat input in the form of Eq. 3 [40].

$$Q = \frac{2\pi\omega\mu P (R_0^3 - r_0^3)}{3} \quad (3)$$

ω : Rotational speed [rpm],
 r_0 : Tool pin radius [mm].

Also, in some works [41–46], numerical modeling has been used to study the peak temperature affected by process parameters. Although the "Coupled Eulerian–Lagrangian Solver" [47]; due to its greater solution accuracy has attracted attention, but the modeling process using this technique is time consuming [48]. Also, Assidi et al. [49] used Arbitrary Lagrangian–Eulerian formulation and automatic remeshing technique to investigate this process.

In this work, for studying the influence of FSP speeds on peak temperature and defects formation, the process

Table 1 AZ91 composition %wt

Al	Zn	Mn	Si	Cu	Fe	Mg
8.3	0.48	0.32	0.02	0.0089	0.0029	Balanced

was modeled using the Arbitrary Lagrangian–Eulerian technique for automatically remeshing of the distorted elements. By determining the thermal distribution and peak temperature, the types of defects can be predicted. The effect of tool rotational and traverse speeds on heat generation during FSP is also investigated since the amount of heat generation decides the material flow in the SZ and hence defects formation [50, 51]. The next sections describe the theoretical background, methodology, the materials, the modeling, etc.

2 Theoretical background

Since FSP is performed in the solid state and no melting or freezing takes place in the SZ, therefore, common defects such as cavities, hot cracks, and freezing cracks observed during traditional fusion processes are not formed during this process. However, specific defects related to this process are produced if the tool design and process parameters are not selected adequately. Normally the defects depending on FSP conditions are the cavity (caused by abnormal stirring), flash, tunnel, voids, groove, cracks (caused by insufficient heat and mixing), pin breakage and pinhole [52] (Appendix).

In this work, two types of defects are studied:

- (1) The flash due to the excessive heat and shoulder pressure;
- (2) The cavity, tunnel, and groove defects caused by insufficient heat and abnormal stirring.

3 Methodology

3.1 Materials and methods

AZ91 cast plates of 350×300×10 mm size have been used in this study. The details this alloy are given in Tables 1 and 2. The tool is of cylindrical shape with a pin of 4 mm diameter and 4 mm length having a flat shoulder with 18 mm diameter. The tool properties are given in Table 3.

During processing, the tool tilt angle was 3 degrees opposite to the processing direction and the plunge depth was 1 mm. The process was conducted on workpieces employing a milling machine (DECKEL FP4M) with several rotational speeds (700, 1000, 1200, and 2000 rpm) and traverse speeds (20, 40, 60, and 80 mm/

Table 2 Properties of AZ91 (at 25 °C) [53, 54]

Properties	Value
Coefficient of thermal expansion [°C ⁻¹]	2.5×10^{-5}
Young's modulus [GPa]	46
Heat capacity [J/Kg °C]	1050
Thermal conductivity [W/mK]	72
Poisson's ratio	0.33
Density [g/cm ³]	1.81
Solidus temperature [°C]	470
Liquidus temperature [°C]	595

Table 3 Properties of H13 tool steel [55]

Properties	Value
Heat capacity (N/mm ² . °C)	2.78
Emissivity	0.7
Thermal conductivity (N/s. °C)	24.5
Poisson's ratio	0.3

Fig. 1 Penetrant liquid leakage from a tunnel defect

min). The processed workpieces were inspected for defects. The conventional quality control examination methods such as non-destructive testing (NDT) techniques including radiography testing (RT) and fluorescent penetrating liquid inspection (PT) were used.

Figure 1 shows the leakage of penetrant liquid from a tunnel defect on the cross section of a processed sample using PT based on ASME-Section V standard; article 6 [56]. The subsurface defects (Fig. 2) could be detected through the RT method of EN1435 standard [57] using XXG300s equipment.

Fig. 2 Subsurface defects detection using RT

Table 4 The Johnson–Cook constants for AZ91 [58]

Parameters	Value
A	108
B	737
C	0.06180
N	0.636
M	2.551

3.2 Numerical modeling to predict peak temperature

Finite element modeling (FEM) based on ABAQUS Explicit has been used to demonstrate the effect of process speeds on peak temperature, thermal distribution, and consequently defects formation. In this model, the workpiece and tool are modeled as deformable bodies and meshed with 3D8RT elements. The Johnson–Cook material law (Eq. 4) was employed to model the material behavior depending on the temperature and hardening. The material/process constants, A, B, C, n, and m are given in Table 4.

$$\sigma = (A + B\epsilon^n) \left[1 + C1n \left(1 + \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right] \left(1 - \left[\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right]^m \right) \quad (4)$$

σ : Equivalent stress [Pa],

ϵ : Equivalent plastic strain,

$\dot{\epsilon}$: Plastic strain rate [s^{-1}],

$\dot{\epsilon}_0$: Reference strain rate [s^{-1}],

T_0 : Room temperature [$^{\circ}\text{C}$],

A: Initial yield stress [MPa],

B: Hardening modulus [MPa],

C: Coefficient depending on the strain rate,

m: Thermal softening coefficient,

n: Work-hardening exponent.

The temperature distribution obtained from FEM has been compared and verified with the results of Parviz Asadi's experimental work [59] with the same parameters defined in this model. In this model, at every time increment, the temperature and displacement for all nodes are evaluated. The critical issue during the simulation of this process is modeling the contact condition between the tool and the workpiece. In this model, the heat transfer through the bottom surface of the workpiece is conducted

by the coefficient of $1000 \text{ W/m}^2\text{K}$. The heat convection coefficient on the surface of the workpiece is $h = 12 \text{ W/m}^2\text{K}$ with the ambient temperature of 25°C . The friction coefficient of 0.3 is assumed between the tool and the workpiece for the penalty contact method. Several traverse speeds of 20, 40, 60, and 80 mm/min and rotational speeds of 700, 1000, 1200, and 2000 rpm were employed during modeling. The total solution time for a full simulation, running on a PC with i3-4150 CPU @ 3.50 GHz and Core (TM) processor was 494 h.

4 Results and discussion

4.1 The mechanism of tunnel defect formation

FSP is a process during which the material flow is laminar, viscous, and non-Newtonian [60]. A previous study [61] shows that during FSP, the material flows vertically and asymmetrically so that in the retreating side region, the material is pushed up, and in the advancing side region, the material is pushed down. In addition, the material in the advancing side region tends to flow in front of the tool, but the material in the retreating side region tends to flow backward.

As mentioned, because of asymmetric material flow in retreating and advancing side regions during tool rotation, at first, cavities are formed in the advancing side region, and immediately material flows from other regions to fill these cavities. If this material flow is insufficient or lagging occurs, the cavities will remain in the stirred zone and when the process finishes; tunnels form and distribute throughout the longitudinal direction of the processing path. The tunnel defects are very sensitive to small variations in process parameters; particularly the tool rotational and traverse speeds and shoulder pressure [62]. The tunnel defects generally appear when the traverse speed is high with respect to the rotational speed used. In this research, the peak temperature of 325°C was obtained when the rotational and traverse speeds were 700 rpm and 40 mm/min, respectively. Under this condition, the tunnel defects formed due to insufficient heat input and inadequate material flow as shown in Fig. 3.

During FSP, tunnel defects are observed in the advancing side, which may be due to insufficient flow of material in the vertical direction, high heat flux on advancing side, and asymmetric flow of plasticized material between advancing and retreating sides [63].

Increase in the axial force, tilt, rotational speed and tool diameter, decrease in the traverse speed and changing the tool configuration cause tunnel defects to decrease [64]. Binit et al. [65] reported that tunnel defects appeared due to limited heat input and insufficient plasticization caused

Fig. 3 Tunnel defect on cross sections of the processed specimen

Fig. 4 Cross section of the processed specimen showing a tunnel defect

by high traverse speed during FSP on aluminum. Increase in the tilt angle and plunge depth and decreasing the traverse speed could eliminate these defects.

The appearance of the mixing zone of the sample with tunnel defect is like a defect-free sample, but as shown in Fig. 4, the tunnel defect can be observed only on the cross section of the sample.

4.2 The mechanism of groove formation

Generally, during FSP; two types of groove defects may be generated due to excessive heat and insufficient forging pressure (type 1, Fig. 5) and insufficient mixing because of insufficient heat (type 2, Fig. 6).

The experimental results show that due to incomplete contact between the tool shoulder and the workpiece, grooves (type 1) can be formed beneath the shoulder where the maximum temperature is observed and

Fig. 5 **a** Groove formed due to insufficient forging, **b** The temperature distribution at **a** 2 s, **b** 5.3 s, **c** 6.6 s, **d** 7.3 s, **e** 7.8 s, and **f** 11 s

Fig. 6 Groove formed due to insufficient heat input

liquation crack occurs (Fig. 5a). In the numerical results, the peak temperature was observed beneath the tool shoulder and at the edge of the tool shoulder as shown in Fig. 5b. This figure shows the thermal distributions at 2 s, 5.3 s, 6.6 s, 7.3 s, 7.8 s, and 11 s during FSP. During this process, the plunge phase and traverse phase happen from 0 to 8 s and from 8 to 18 s, respectively. This comparison indicates the good agreement between the numerical and the experimental results.

Accordingly, grooves (type 1) are formed due to low traverse speed or high rotational speed and insufficient shoulder pressure. In other words, when the peak temperature is above the softening temperature and the tool pressure is not enough, this defect forms. It seems that the shoulder pressure cannot forge and join the material behind the tool. For eliminating these defects, the shoulder pressure should be increased and the ratio of ω/v

should be decreased. Sumit et al. [66] reported that during FSP on aluminum, high heat inputs cause over plasticization and formation of groove defects. Zand Salimi [67] also indicated that grooves form during FSW of AA6061 and 430 stainless steel, because high input produces a plasticized material in the SZ which cannot be maintained by the tool shoulder.

On the other hand, the grooves (type 2) form due to insufficient stirring. Rotation of the tool causes softening, mixing and forging of the material. During FSP, sufficient heat must be provided by the plastic deformation and frictional energy to accomplish the process. To prevent formation of these process defects (groove-type 2), it is necessary to generate enough frictional and deformation energy. Coefficient of friction, speed of tool rotation, shoulder pressure, and the tool-workpiece contact area affect the frictional energy. Therefore, grooves (type 2) as shown in Fig. 6, may form due to insufficient heat input (low peak temperature). Because of small shoulder diameter, incomplete contact between shoulder and workpiece,

high heat conductivity, and the low ratio of ω/v , enough heat is not generated. Habib Nia et al. [68] reported that these groove defects formed due to low shoulder penetration in FSW of AA5050 and 304 stainless steel. They indicated these defects could be prevented by using higher shoulder penetrations up to 0.4 mm. Excess shoulder pressure however causes flashes. In a similar study, Das et al. [69] also concluded that low frictional heat generation led to poor plasticization of material and inadequate stirring of the material. This can be a reason of defects formation in the weld.

In this research, a peak temperature of 503 °C was obtained with the linear speed of 20 mm/min and tool rotation of 700 rpm (Fig. 7a). However, increase in the linear speed to 60 mm/min caused the peak temperature to drop to 257 °C (Fig. 7b). The insufficient heat generated led to the formation of the groove defects (type 2) in the workpiece as shown in Fig. 6. Therefore, at traverse speeds of more than 20 mm/min and the tool rotation of 700 rpm, the heat induced by plastic deformation and

Fig. 7 The peak temperature predicted by numerical modeling

- a** Traverse speed = 20 mm/min
Rotational speed = 700 rpm
Peak temperature = 503 °C

- b** Traverse speed = 60 mm/min
Rotational speed = 700 rpm
Peak temperature = 257 °C

frictional contact is not high enough to cause sufficient material flow and completely merge the material behind the tool. Thus, according to the numerical results and experimental observations, a defect-free workpiece can be produced with traverse speeds of more than 20 mm/min when the rotational speed is 700 rpm.

In a similar research Kim et al. [70], could produce a defect-free joint with the tool plunge downforce of 6.9 kN and the traverse speed of 250 mm/min. However, with increasing the speed to 500 mm/min, process defects were observed. At higher transverse speed of 750 mm/min, the groove defects appeared in the SZ.

4.3 The mechanism of flash formation

During FSP; the heat generated because of SPD and frictional contact causes the workpiece to experience a temperature above its melting point and therefore the material behind the shoulder softens excessively. If the pressure exerted by the shoulder is high, the material ejects as a flash. Consequently, this defect leads to the thinning of the material in the SZ. Kim et al. [72] reported that formation of flash takes place when excessive heat is generated due to low traverse speed, high rotational speed and high pressure. In Fig. 8, the formation of flashes in the advancing side region with the traverse speed of 20 mm/min and rotational speed of 2000 rpm is shown. Also, as shown in Fig. 9, during this test, the peak temperature in SZ is 632 °C. Therefore, these results show that unlike the work reported by some researchers [71, 72], increasing the tool rotational speed does not always lead to better mechanical properties because of the flash formed.

The numerical modeling shows that during FSP; with the tool rotation of 1200 rpm and the linear speed of 60 mm/min (speed ratio of 20), a peak temperature of 475 °C occurs. At this temperature, the material softened and no large-scale melting zone was observed. In Fig. 10, the defect-free specimen processed under these conditions is shown.

Fig. 8 Flash formed during FSP

Traverse speed = 20 mm/min
Rotational speed = 2000 rpm
Peak temperature = 632 °C

Fig. 9 The peak temperature predicted by 3D numerical modeling

4.4 Microstructural evolution after FSP

To investigate the effect of FSP on microstructure, the base metal and processed samples were polished and etched according to the related standard [73]. The microstructure of samples was investigated with scanning electron microscopy (SEM) and optical microscopy (OM). As shown in Fig. 11, before FSP, the base metal microstructure consists of rough grains (dark dendrites observed in α -Mg field) and the lattice network of β -phases.

After FSP with the tool rotation of 1200 rpm and the linear speed of 60 mm/min, the microstructure equiaxed, and the eutectic networks converted to small particles (Fig. 12). In Fig. 12b and c, it is observed that; although the structure has improved, but in the SZ down, grains were finer than those of the SZ up of the nugget. This may be due to the intense deformation beneath the shoulder and equiaxed recrystallized structure in the nugget zone that experienced SPD at a high strain rate. In a similar study, Cerri et al. [74] mentioned that FSP of Mg alloy caused the disappearance of porosity and the formation of very fine grain boundary phases.

Rotational speed = 1200 rpm
Traverse speed = 60 mm/min

Fig. 10 The defect-free specimen

Fig. 11 The microstructure of the cast workpiece

Using the CLEMEX commercial software for grain size measurement, the average grain size of the cast sample was found to be about 98 μm . The nugget zone grains refined to about 23 μm after FSP. In a similar research, El-Danaf et al. [75] studied the FSP influence on AA5083 grain size and hardness. They concluded that after FSP, the grain size decreased but hardness increased. Nascimento et al. [76] performed one and multi-pass FSP on an aluminum alloy for obtaining a uniform hardness profile in the SZ. Wenya et al. [77] indicated that increase in rotational speed increased the average grain size but decreased the mechanical properties.

The cross sections of the friction stir processed workpieces at various tool rotations are shown in Fig. 13. As shown in this figure, increase in the tool rotational speed, increases the width of the SZ and HAZ; which may be attributed to the introduced severe plastic strain and generation of higher heat input. Similar results have been reported after performing FSW on AZ31 [78] and FSP on aluminum alloys [79, 80].

4.5 The tensile test results

Several processed and base metal specimens were taken for performing tensile tests using a universal testing machine. The tensile test results are given in Table 5. As shown, after FSP under optimized speeds, the yield strength (YS) and the UTS of the processed specimens increased by about 17% and 22% compared to YS and UTS of the cast specimen. This may be mainly due to the refinement of the microstructure, elimination of casting defects (especially porosities), and decreasing the grain size in the SZ. In a related research [81], it was observed that; FSP results in significant grain refinement, breaks the β -phase networks into small particles, and improves

Fig. 12 The microstructure of the processed sample (a) using SEM, b the SZ down, c the SZ up

Fig. 13 Cross-sectional macrostructure of SZ at different rotational speeds: a 1200 rpm (lap width = 20 mm) (b) 1000 rpm (lap width = 14 mm)

the superplasticity. The experimental results show with decreasing the rotational speed, the YS and UTS decrease due to insufficient material flow. In a related study, Feng et al. [39] indicated that grain size reduction, eliminating

Table 5 The tensile test results

Test condition Unit	Rotational speed [rpm]	Traverse speed [mm/min]	Ultimate stress [MPa]	Yield stress [MPa]
Base workpiece at ambient temperature	–	–	214	112
Friction stir processed workpiece at ambient temperature -perpendicular to the processing path	1200	60	105	55
Friction stir processed workpiece at ambient temperature—parallel to the processing path	1200	60	262	132
Friction stir processed workpiece at ambient temperature—parallel to the processing path	1000	60	195	110
Friction stir processed workpiece at ambient temperature—parallel to the processing path	700	60	103	64

defects, and dissolution of the unstable intermetallic network into the matrix cause increase in strength. Moreover, due to the DRX, the density of dislocations reduced and tensile strength decreased [82]. Therefore, these factors affect the hardness and tensile strength of the processed workpiece. To analyze the strain hardening behavior, Wenya et al. [79] explained several reasons for improving/decreasing the strength of workpieces after stationary shoulder FSW (SSFWS). Increase of low hardness zones in thermomechanically affected zone (TMAZ) affected the tensile properties of magnesium alloys [83]. In addition, residual stresses, dislocations density in the processed zone, and non-uniform dispersal of texture in SZ [84, 85] affected mechanical properties after processing. They concluded that the possible reason for better mechanical properties of the processed samples may be due to microstructure refinement.

5 Conclusions

To produce defect-free and high-quality friction stir processed workpieces, the process parameters; particularly tool rotational and traverse speeds (or the ratio of rotational speed to traverse speed) which affect heat generation during the process must be properly controlled. To achieve these aims, experimental and numerical investigations on occurrence of defect formation, microstructure and tensile strength of AZ91 magnesium alloy samples processed under various rotational and traverse speeds were carried out.

Using finite element method, a 3D thermo-mechanical model has been developed and used to investigate the influence of tool speeds on thermal distribution and peak temperature. The Johnson-Cook models were employed for defining the material behavior and the failure criterion. Experiments were conducted to validate the proposed model. The major findings drawn from this study are:

The developed model can explain and predict the influence of process speeds on peak temperature, thermal distribution and FSP defects.

A defect-free sample was obtained when the ratio of rotational speed to linear speed was 20 ($\omega = 1200$ rpm, $v = 60$ mm/min.) and maximum temperature was 475 °C.

At ω/v of 100, a peak temperature of 632 °C was reached in the SZ that was more than the melting point of the alloy. Experimental observation showed that flash defects were formed with this ratio. Decreasing the ω/v to 17.5 caused a reduction in the peak temperature to 325 °C which was lower than the softening temperature and led to incomplete stirring and hence the tunnel defect formation.

Type-2 groove appeared when rotational speed decreased from 1200 to 700 rpm at the constant traverse speed of 60 mm/min. (ω/v decreased from 20 to 11.6).

Numerical modeling showed that when ' ω ' increased from 700 to 2000 rpm (at $v = 20$ mm/min.), the variation of the maximum temperature was about 246 °C (503–632).

When ' v ' increased from 20 to 60 mm/min. (at $\omega = 700$ rpm), the variation of the maximum temperature was more than 246 °C (503–257).

Experimental results indicated that YS and UTS of the processed sample were more than that of the base metal by about 17% and 22% with the tool rotation of 1200 rpm and linear speed of 60 mm/min.

As a result of FSP, grain size in the nugget zone refined to about 23 μm compared to 98 μm of the cast plate.

HAZ and SZ width increased when the rotational speed increased.

FSP is a complex process with increasing scope that needs further research. Metallurgical and numerical investigations on material flow around defects can be recommended.

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Author contributions BN did the casting and provided the AZ91 cast plates. HA prepared other materials, conducted the experiments and modeled the process under the supervision of other authors. She wrote the initial manuscript and NBMA finalized the manuscript. All authors have approved the manuscript.

Data availability Not applicable.

Code availability Office, Grapher, ABAQUS 6.13–4.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Appendix

When the pin doesn't break during the FSP process, it leaves an empty space (pinhole) at the end of the process path. The pinhole is a defect and causes stress concentration. On the other hand, if the pinhole does not exist, it indicates that the pin is broken during the process and no effective mixing has occurred in the stirred zone. The pin breakage takes place in two different ways. The pin may break inside the workpiece and; the tool moves until the end of the path, or the pin breaks and the broken piece reaches the surface of the workpiece.

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