Numerical modeling and experimental investigation of brass wire forming by friction stir back extrusion

Parviz Asadi1 · Mostafa Akbari2

Received: 22 March 2021 / Accepted: 12 July 2021 / Published online: 19 July 2021
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
Friction stir back extrusion (FSBE) is used to produce brass wires, and then numerical modeling is developed to model the process by the coupled Eulerian-Lagrangian (CEL) technique and verified by experiments. Next, the effects of FSBE parameters, including tool rotational and plunging speed, on the strain and temperature distributions, microstructure, and material flow patterns are studied. The results show that the highest temperature and strain occur near the tool/workpiece interface but at a further distance from the tool axis. Additionally, in the cross section of an FSBE wire, the microstructure is more refined in the sample’s periphery. A higher rotational speed or a lower plunging speed results in a coarser microstructure. The material flow pattern is a conical helix and does not change meaningfully by the process parameters. The points at the further distance from the tool axis, along with an upward movement, experience an inward spiral motion which is amplified by higher rotational speed. However, the materials near the tool axis almost take an upward movement and endure a significantly lower strain.

Keywords FSBE · Wire extrusion · Microstructure · FEM · Material flow

1 Introduction

The brasses (Cu–Zn alloys) contain 5 to 45% of zinc to donate a higher hardness and mechanical resistance to the brass, while the rest is copper, giving a higher corrosion resistance for many mediums [1, 2]. Therefore, these alloys have various mechanical and physical properties based on their Zn content. Also, they may have a small amount of iron, lead, and other trace elements. Furthermore, brasses have high thermal and electrical conductivities, high malleability, a good combination of strength and ductility, high corrosion resistance, good castability and formability, and excellent machinability [2, 3]. These remarkable and unique properties have widespread applications of brasses in different fields such as low-pressure valves, plumbing fittings and fixtures, counters and taps, bearings, gears, architectural frames and decorative hardware, musical instruments, and germicidal and anti-microbial devices [4, 5].

Due to the limited resources, high energy consumption, and environmental contamination, metal recycling has become an essential topic these days. The copper, aluminum, iron, etc., based metals and alloys are broadly utilized to manufacture almost all kinds of industrial products. Therefore, the metal chips produced during machining are the majority of waste materials in industrial firms [6]. Additionally, every year, many metal scrap pieces are produced in the shops, which are then chopped up with shredders into chips. Although these wastes are mostly polluted with oils and cutting fluids, the washing costs are significantly lower than mining them. Generally, for recycling, the metal chips are re-casted [6, 7]. In this way, some companies are needed for collecting the chips and transferring them into the casting shops, and again rolling, extrusion, and other processes are required to produce the final/usable metal product. However, new recycling techniques have emerged by technological advancements, such as the friction stir back extrusion (FSBE), enabling the shops to recycle the metal chips into extruded products directly.

Previously, friction-based processes such as friction welding methods have demonstrated their capability in joining and forming the materials in solid state and have introduced...
products with desired mechanical properties [8–11]. Recently, a new friction stirring concept was developed, which targets the recycling and processing of chips to generate a bulk material. The FSBE as a solid-state recycling technique produces frictional heat to soften the recycling chips, and then, by applying adequate pressure as a forging force, the chips are merged and pushed to a channel to produce an integrated product like a wire or tube.

Abu-Farha [12] applied the FSBE process to produce aluminum tubes and observed a fine-grained microstructure along the tube wall. Dinaharan et al. [13] explained how the FSBE could be applied to deform the solid cylindrical pure copper ingots to defect-free tubes. Their microstructural observations showed that the produced copper tubes belong to a homogenous microstructure along the tube, but the trapped frictional heat made the grains coarse. So, they concluded that adequate heat dissipation during FSBE is required to control the evolution of the microstructure. Similarly, Mathew et al. [14] produced seamless aluminum tubes by deforming the solid cylindrical bars utilizing the FSBE. They indicated this process is capable of producing defect-free aluminum seamless tubes. Zhang et al. [15] deformed hollow cylindrical billets of 6063-T6 aluminum alloy to tubes by FSBE and found equiaxed refined grain structure as a result of dynamic recrystallization. They reported that the grain size is reduced from ~58 μm in the base metal to 20.6 μm at the tube’s inner wall. However, the microhardness declined from 100 to 60–75 HV due to the thermal process cycle.

In terms of finite element modeling (FEM) of FSBE, some endeavors are reported in the literature in recent years. Behnagh et al. [16] presented a 2D thermo-mechanically coupled Eulerian-Lagrangian model using the Abaqus software to simulate the FSBE process for the production of pure magnesium alloy wires while the work hardening and strain softening effects were taken into consideration in the model. Additionally, they modeled grain size evolution based on the dynamic recrystallization (DRX) kinetics laws. Baffarî et al. [17] proposed a 3D Lagrangian thermo-mechanically coupled numerical model using the DEFORM3D software for FSBE of AZ31 magnesium wire and approved the model by temperature measurements. They also investigated the process mechanics to attain information on the material flow over the process as well as on the final product surface quality as a function of the tool plunging force and rotational speed. Additionally, in another work [18], they investigated the effect of process parameters and extrusion rate on the temperature and strain distribution.

In the present research, a brass shaft is formed using FSBE to produce integrated solid wires, and the effects of rotational and plunging speeds on the mechanical and microstructure properties of produced brass wires are investigated. Additionally, the CEL method is proposed to model the FSBE numerically for brass wire production. The model is validated based on the acquired experimental temperature data, and then the effects of process parameters on the strain and temperature distributions as well as the material flow patterns are investigated. The regions with the highest temperature and strain are identified, based on which the material flow and the achieved experimental microstructures are justified.

2 Experimental procedure

The principle of the FSBE process is shown in Fig. 1. The experimental setup consists of three main parts: a rotational tool, a matrix, which acts as a storage for the chips, and some raw material as chips or bulk. The matrix is fixed on the milling machine table. In order to better guide the material into the central hole, the tool surface in contact with the material is made sloping. In this process, the chips are placed inside the matrix. The rotating tool then enters the matrix with a specified traverse speed. A vast amount of friction-induced heat is generated due to the rotation and translation along the feed direction, which softens and fully consolidates the chips. The softened chips enter the tool and come out in the form of wires.

In the present work, a CuZn39Pb2Sn brass shaft, with the chemical composition listed in Table 1, was inserted into the mold cavity (matrix) prior to applying the FSBE process. The matrix was made from H13 steel and then heat treated to attain 52 RC hardness (Fig. 2a). The FSBE tool, with the outer and inner diameters of 30 and 7 mm, was made of chrome-nickel steels and heat treated to achieve 58 RC hardness. The tool

![Fig. 1 Schematic representation of the FSBE process](image-url)
head contains a 30° conical concave toward the central hole for easier flow of the softened material from the primary material toward the sizing channel for the wire. The FBE tool picture is shown in Fig. 2b. A cylindrical brass stock, with the diameter and height of 30 and 40 mm, was used as the primary bulk material.

The tool and matrix dimensions were constant in the present work, but the main process parameters of tool rotational and plunging speeds were varied to observe their effects on the mechanical and microstructural properties of produced brass wires. The rotational and plunging speeds were varied between 315 and 800 rpm and 25 and 40 mm/min, respectively. Some of the produced brass wires by FSBE process are shown in Fig. 2c.

To acquire the temperature history during the process, a four-channel thermometer was used, and the thermocouples were inserted in the radial 4-mm holes on the matrix body with different spaces from the top edge.

For microstructural observations on the optical microscope (OM), the wires are cut perpendicular to the wire axis and polished using a standard procedure. The prepared metallographic samples are etched with a solution of 5 g FeCl₃, 30 mL HCl, and 100 mL ethanol in 20 s, and then washed with distilled water and dried.

Table 1 Chemical compositions of CuZn39Pb2Sn brass used in this study

| Element | Cu  | Zn   | Pb   | Sn   | Fe  | Ni  | Al  | Mn  | Si   | S   | P   |
|---------|-----|------|------|------|-----|-----|-----|-----|------|-----|-----|
| % wt.   | 58.9| 37.39| 2.14 | 0.60 | 0.51| 0.43| 0.007| 0.004| 0.003| 0.003| 0.003|

3 Model description

The first important principle in the numerical simulation of processes involved large deformations in the mechanics of nonlinear solids using an appropriate kinematic description for the deformation of the continuous environment. The two main classical views for the kinematic description of the continuous environment are the Lagrangian view and the Eulerian view. In the Lagrangian view, the configuration network adheres to the material and follows the deformation of the material. This view is widely used in the field of solid mechanics and is especially suitable for problems involving unrestrained flow at free boundaries and interference between different materials and materials for which the history of deformation is essential because the grid accurately represents the boundaries of matter during analysis. Network and element distortions are severe complications of using this type of networking.

In the second view, the configuration network is fixed in the desired space, and the flow of matter passes through the network components. In general, this method is a realistic view of fluid mechanics problems containing a volume of control. In the field of solid mechanics, this configuration is suitable for steady-state analyses of forming processes in
which the material flow is high but has the least deformation on the free boundaries in the boundary shape. But because the network remains constant, it is not easy to model the deformation on the free boundaries that develop during the deformation with this method. In general, the Eulerian method is not suitable for analyzing the areas with moving borders due to the inaccurate expression of free boundaries.

From the explanations given, it can be concluded that none of the Lagrangian and Eulerian views alone is suitable for modeling severely deformed processes such as friction stir extrusion. In fact, the strength of each is the weakness of the other method, and both methods are complementary. Therefore, new configurations that can combine Lagrangian and Eulerian networking benefits are more suitable for simulating the friction stir extrusion process.

Two methods, namely the arbitrary Eulerian-Lagrangian (ALE) and the CEL, are among the methods combining the advantages of these two types of networking. The ALE method is a kind of finite element networking in which the network components in the space are neither fixed nor connected to the object or material but have the desired motion. In other words, this method is a combination of the two mentioned networking in which the network components and material have relative motion.

Therefore, each of the network components and the material configuration can move independently. This feature of the ALE method is a powerful tool for modeling processes in which large and severe local deformations occur in the material, and there is a large unrestricted flow across free boundaries. In this way, ALE can be transformed into Lagrangian on free boundaries, but in areas where large deformation occurs, it can be Eulerian.

The CEL method is another finite element networking used in processes with severe plastic deformation, such as friction stir extrusion. In this method, the sample is modeled using Eulerian relations, which prevents severe network distortion. The tool is also modeled using Lagrangian relations, which prevents severe friction stir extrusion. In this method, the sample is assigned in the upper region and Eulerian networking benefits are more suitable for simulating the friction stir extrusion process.

The ABAQUS software was utilized to simulate the material flow and temperature history during the FSBE of brass. A CEL method is utilized in this study to simulate various aspects of the process. In this method, the finite elements are fixed in space, while the material could flow through these elements [19]. As a result, no mesh distortion usually existed in the Lagrangian methods. The tool is defined as a rigid Lagrangian body, and the workpiece was modeled as an Eulerian part with EC3D8RT elements.

The Eulerian part has been considered as a cylindrical shape that includes two sub-regions: “full” and “void.” The lower region “full” is predefined with the brass, and no material is assigned in the upper region “void” to identify the movement of the material during the process. The material layout used in the present model to produce the brass wires is shown in Fig. 3. The dimensions of tool, matrix, and primary stock are selected as those described in the experimental section. The void height in Fig. 3 for the primary stock is taken as 50 mm.

### 3.1 Governing equations

In the CEL method developed in this study, Eulerian formulation, where energy, mass, and momentum are conserved, is utilized to model the workpiece domain.

The equation of mass conservation (Eq. 1) represents the rate of outflow mass and mass changes inside the control volume.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}
\]

Where \( \rho \) and \( \mathbf{v} \) are the density and velocity of the material, respectively, the conservation equation for momentum (Eq. 2) equals the change of momentum of the domain to the sum of the spatial time derivative of the gravitational force and the Cauchy stress tensor.

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \nabla \cdot \mathbf{\sigma} + \rho \mathbf{g} \tag{2}
\]

Where \( \mathbf{\sigma} \) and \( \mathbf{g} \) are the Cauchy stress tensor and the gravity constant, the energy conservation equation incorporates the rate of plastic work done on any element, the heat flux into elements as a result of conduction, and the generation of the volumetric heat from the element.

\[
\rho C_p \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = \nabla \cdot (K \nabla T) + \nabla \cdot (\mathbf{\sigma} \cdot \mathbf{v}) + Q \tag{3}
\]

Where \( K \), \( C_p \), \( T \), and \( Q \) represent the thermal conductivity, the material-specific heat, the temperature in the Kelvin scale, and the volumetric heat generation rate. The Eulerian-based equations (Eqs. 1–3) have a general conservation form as below:

\[
\frac{\partial \Phi}{\partial t} + \nabla \cdot \Phi = S \tag{4}
\]

Where \( S \) and \( \Phi \) are the source term and the flux function, respectively. The operator splitting algorithm splits the governing equation (Eq. 4) into Eulerian step containing the flux function term \( \Phi \) and Lagrangian step containing the source term \( S \), as shown in Eqs. 5 and 6. The CEL method
solved these two equations sequentially. Figure 4 schematically illustrates the split operator for each step of the CEL method.

\[
\frac{\partial \varphi}{\partial t} = S \tag{5}
\]

\[
\frac{\partial \varphi}{\partial t} + \nabla \cdot \Phi = 0 \tag{6}
\]

### 3.2 Material model

The material flow stress in FSBE is a function of strain, strain rate, and temperature. Therefore, Johnson-Cook’s model (JC) is used as the material flow model of brass as follows:

\[
\sigma = (A + B \varepsilon^n) \left(1 + C \ln \left(\frac{\varepsilon}{\varepsilon_0}\right) \right) \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \tag{7}
\]

Where \(A, B, C, n,\) and \(m\) are constants related to the material, \(T_m\) is melting temperature (from Table 2); \(T_r\) is the ambient temperature, \(\varepsilon\) represents the plastic strain; \(\varepsilon_n\) the normalizing strain rate; and \(\varepsilon_p\) is the effective plastic strain rate. The first term of Eq. 7 is the power law that defines plastic training influences on the flow stress. The second and third terms of the equation considered the effect of the strain rate and temperature. Table 2 illustrates Johnson-Cook’s parameters for brass alloys [20–22].

### 3.3 Contact interactions and boundary conditions

The primary sources of heat generation during FSBE are plastic deformation and friction where \(\dot{Q}_F\) and \(\dot{Q}_P\) are friction and plastic deformation heat generation, respectively. The friction heat generation is the tangential stress and slip-rate product at the interface, as expressed by Eq. 9. Moreover, the amount of material deformation determines the heat generation because of plastic deformation as shown in Eq. 10.

\[
\dot{Q}_F = \phi \left(\tau \times \gamma\right) \tag{8}
\]
In this way, the penetration of workpiece nodes into the tool is minimized; and thus, the compressive stress at the interface drops down to zero. Reversely, the separated surfaces come into contact when the clearance between them becomes zero. Moreover, heat dissipation because of convection occurred from the workpiece surfaces to the air:

\[
\dot{Q}_p = \eta (\sigma \times \varepsilon)
\]

Where \(\sigma\) is flow stress, \(\phi\) is frictional heat factor, \(\varepsilon\) represents strain-rate, \(\eta\) is inelastic heat fraction, and \(\gamma\) is slip-rate, respectively. Moreover, heat dissipation because of convection across the interface and the pressure of contact in the contacting bodies. In the basic form of the Coulomb friction model, two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to one another; this state is known as sticking. The Coulomb friction model defines this critical shear stress \((\tau_{\text{crit}})\) at which sliding of the surfaces starts as a fraction of the contact pressure \((p)\) between the surfaces \((\tau_{\text{crit}} = \mu p)\). The stick/slip calculations determine when a point transitions from sticking to slipping or from slipping to sticking. The fraction \((\mu)\) is known as the coefficient of friction. There are different models in order to define the coefficient of friction. In this investigation, the penalty equation was used to model tangential behavior with tools and materials and defines the friction coefficient. In this model, the coefficient of friction is a constant value that is determined by the process conditions. Also, the normal contact between tool and material is modeled by the hard contact pressure enclosure to minimize the penetration of workpiece nodes into the tool. In this model, when surfaces are in contact, the resulted pressure will transmit between the surfaces. They are separated if the contact pressure drops down to zero. Reversely, the separated surfaces come into contact when the clearance between them becomes zero. In this way, the penetration of workpiece nodes into the tool is minimized; and thus, the compressive stress at the interface can be defined. Through the contact interactions, the Eulerian body is coupled to the Lagrangian.

### 3.4 Meshing

Thermally coupled eight-node linear Eulerian brick elements (EC3D8RT) with reduced integration are utilized to mesh the Eulerian domain. Fine mesh is a crucial parameter to achieve an accurate model of FSBE. Moreover, a coarse model in the CEL method leads to Eulerian material flowing through the Lagrangian mesh and decreases accuracy [10]. As different mesh sizes were investigated, a fine mesh with the mesh size of 0.8 mm is selected (Fig. 5).

The rotating tool and the matrix are modeled as the Lagrangian rigid body and meshed with the thermally coupled 4-node 3D bilinear rigid quadrilateral elements. All tool movement conditions are assigned with respect to the tool reference point to precisely control the tool movement.

### 4 Results

First, the model is verified by the thermal history curves, and then, the experimental investigations, such as microstructures along with the numerical results such as temperature and strain distributions and material flow, are discussed in the following subsections.

#### 4.1 Numerical model validation

To verify the model accuracy, the simulation and experimental thermal history curves are compared (Fig. 6). The temperatures are acquired on the matrix body with a 3-mm distance from the inside cylindrical surface and a 10-mm distance from the top surface. Figure 6a shows the temperature distribution on the matrix body when the tool is penetrated almost 10 mm on the matrix hole (5 mm into the workpiece) with the rotational and plunging speeds of 800 rpm and 25 mm/min. As can be seen, a severe thermal gradient occurs on the matrix body, and thus, its substance, not as much as a rotating tool but is critical to withstand this thermal gradient.

Figure 6b shows the experimental and numerical temperature history curves over the process. As can be seen, a good agreement is achieved between experimental and numerical results. Although the maximum temperature in the matrix body reached almost 600 °C, it would be much higher in the tool/workpiece interface.

#### 4.2 Temperature distribution

Figure 7 shows the temperature distribution for the workpieces under extrusion by different tool rotational and plunging speeds. In the FSBE, similar to other friction-stir-based
The effects of tool rotational and plunging speeds on the temperature distribution are clearly shown in Fig. 7. By increasing the plunging speed from 25 to 40 mm/min while the rotational speed is constant at 800 rpm, the maximum temperature drops down from 860 to 780 °C (Fig. 7a–c).

On the other hand, the rotational speed is changed from 800 to 315 rpm at the constant plunging speed of 25 mm/min, and the results are demonstrated in Fig. 7a and d–f. By reducing the rotational speed, generation of both the frictional and plastic deformation heat diminishes. It is shown that the maximum temperature declined from 860 to 650 °C by decreasing the rotational speed from 800 to 315 rpm.

The temperature variation curves along the horizontal straight line, which crosses over from the tool edges, are shown in Fig. 8. As shown in the figure, in each curve, the highest temperature emerges in the workpiece/tool contact point, and going toward the sample center, the temperature declines. By comparing the maximum temperature achieved in different process parameters, it can be deduced that the
samples with higher rotational speed to plunging speed ratio ($\omega/v$) show a higher maximum temperature. Additionally, it is clear that the difference between the maximum temperature at the outer point of the workpiece and the minimum temperature at the center of the workpiece becomes deeper at higher plunging speeds. In other words, the depth of the bowl-shaped curve is deeper at the higher plunging speeds; and thus, it generates a higher temperature gradient inside the workpiece.

### 4.3 Strain distribution

Along with the thermal cycle and maximum temperature, under process substance experiences, the plastic deformation aspects such as effective strain and strain rate affect the microstructure and, therefore, the product’s mechanical properties. Furthermore, the amount of strain applied to the material during the friction-stir–based processes is very much higher than the other severe plastic deformation (SPD) processes [26]. For instance, the maximum amount of strain can be applied by the different types of extrusion, equal channel angular process (ECAP), and incremental forming (IF) processes are 1–5 [27]. In contrast, it is varying between 50 and 200 in the FSW process, based on the tool geometry and process parameters [28–30]. Therefore, study on the strain plays a crucial role in considering and determining the microstructural properties of the produced materials by FSBE. Figure 9 describes the effects of the rotational and plunging speeds.

![Fig. 7 Temperature distribution in the samples produced with different rotational and plunging speeds](attachment:image1)

![Fig. 8 Temperature variation curves along the horizontal straight line which crosses over from the tool edges (the image on the right top corner)](attachment:image2)
on the strain distribution. It should be mentioned that all of the plotted results for Figs. 7, 8, and 9 are obtained for the same punch penetration.

As it was expected, in all of the samples, the maximum strain occurs in the tool/workpiece interface and is the highest near the outer edge of the tool (Fig. 9). Indeed, going far from the tool center increases the tool center’s sweeping capability, which boosts both the frictional heat and plastic deformation, and these two results invigorate each other. Because the higher the temperature, the softer the material, and thus, the easier the material movement and the higher the strain.

Comparing Fig. 9a–c, one can be concluded that an increase in the plunging speed leads to a decrease in the amount of strain which the material under process experiences. Although by increasing the plunging speed, the process force increases, the processing time declines, and a distinct point inside the material experiences the deformation in a lower amount and lower time. At the constant rotational speed of 800 rpm, when the plunging speed goes up from 25 to 40 mm/min, the strain decreases from 55 to 38 mm/mm.

It is clear that a decrease in rotational speed results in a lower strain in terms of the rotational speed, as the strain amount from 55 mm/mm at the rotational speed of 800 rpm drops down to 35 mm/mm at the rotational speed of 315 rpm. Consequently, a lower \( \omega/v \) results in a lower strain because a distinct point inside the material experiences lower plastic deformation over the process.

### 4.4 Microstructures

Figure 10 shows the base metal microstructure and the produced samples at different rotational and plunging speeds. Figure 10a illustrates the microstructure of base metal used in this study with a grain size of almost 18.5 \( \mu \)m. Regarding the produced wires by FSBE, since the center and periphery of the produced wires experience different amounts of strain and temperature, the microstructure images are shown at the center and periphery of wires. Figure 10b shows the locations on the cross section of a wire from which the microstructure images are taken. Different affecting factors can determine the grain size at the resulted microstructure. The amount of strain and the temperature history are the most affecting factors on the microstructure of FSBE samples. The higher strain will result in a higher dislocation density and more preferential sites for grain nucleation and consequently will produce a microstructure with more refined grains [31–33]. As cited before, the amount of produced strain in the FSBE process is very high; and therefore, it is expected to generate a microstructure with ultrafine grains. However, as shown in Fig. 10, there is no significant difference between the grain size of base metal.
and the produced FSBE samples. While the grain size in the base metal is almost 18.5 μm, it varies between 10 and 30 μm in the produced samples by FSBE.

Besides the strain value, the materials’ temperature during the FSBE is higher than that of the other SPD processes. While the cold extrusion, ECAP, and IF processes are generally applied at the ambient temperature (or a bit higher), in the FSBE process, the temperature sometimes rises to 95% of the material melting point. These very high temperatures could severely diminish the effects of strain on the microstructure by growing the grains, even if several continuous dynamic recrystallizations occurred.

Figure 10c shows the microstructures of the produced brass wire, using FSBE by the rotational and plunging speeds of 800 rpm and 25 mm/min, at the sample center and periphery. As can be seen, the grain size at the center is 28.3 μm, while it is 27 μm at the sample periphery. The materials at the periphery of the wire have mainly come from the outer layers of initial stock (will be discussed later) and experience higher strain than the materials at the center. Therefore, from the
strain point of view, the grains at the sample’s periphery should be more refined than the center. In terms of temperature, although the material at the periphery has experienced a bit higher temperature, it is almost uniform when the materials are crossing from the sizing channel (the central hole of 7 mm dia.). Additionally, when the wire passed this channel, the periphery temperature could be lower due to the thermal conduction. Consequently, it seems that the strain is the dominant factor for the microstructural deviation in the sample cross section rather than the temperature.

The effect of plunging speed on the microstructure and grain size is shown in Figs. 10c–e and 11a. By increasing the plunging speed from 25 to 40 mm/min, although the strain amount applied to the materials is decreased (Fig. 9), it seems that a 90 °C temperature drop is more effective than the strain decrease as the grain size is reduced almost 8 and 10 μm at the center and periphery of the samples, respectively. Also, along with the temperature reduction, by increasing the plunging speed, the time that the material endures the higher temperatures reduces, which helps in grain growth prevention.

Figures 10c and f–h and 11b show the effect of rotational speed on the microstructure and grain size at the center and periphery of FSBE samples. It can be seen that the grain size is reduced from 28.3 to 12.21 μm (for the sample center) by decreasing the rotational speed from 800 to 315 rpm. Like the plunging speed, the temperature is the dominant factor rather than the strain that the material experiences over the FSBE process.

Generally, it can be concluded that:

1. When the process parameters are constant (means in a sample), the microstructural deviation at the sample cross section is mainly affected by the strain. However,
2. When the process parameters are changed (means from one sample to the other), the temperature is the dominant factor in grain size.

Furthermore, paying attention to Fig. 11a and b, it can be deduced that at the lower \( \omega/v \) ratios, the difference between the center and periphery grain size becomes more tangible. It seems that at the higher \( \omega/v \) ratios, along with the rising peak temperature, the effect of strain on the cross-section microstructural deviation becomes weaker.

4.5 Material flow

The material flow phenomenon is one of the most critical issues in the FSBE process since a weak material flow can result in several types of defects in the produced wires. Deeper investigations are needed to achieve optimum material flow ranges based on the process parameters such as rotational and traverse speeds, tool design aspects including the head angle, head profiles, and etc. A strong material flow could be a sign for producing a defect-free sample with a more refined and more homogeneous microstructure. The developed numerical model is capable of considering the material flow during the FSBE process of brass. The point tracking technique of the ABAQUS software is used to study the material movement as well as the effects of process parameters on this movement.

To study the material flow pattern during the FSBE process, the moving paths of 3 different points located at different distances from the tool axis are considered. In Fig. 12a–c, the points are located at 1, 3, and 5 mm from the central axis in the initial stock. Their paths over the process from initial stock to final wire sample are observed from 3D, front, and top views. As can be seen, all points rotate around the axis and go up in an almost helical path from the initial stock into the sizing channel to produce the wire. However, the path for the point at a 1-mm distance from the center is almost pure helical and moves almost upward with a lower speed, while, for the point at a 5-mm distance from the center, the path is conical helix and, besides the upward movement, takes an inward spiral movement; and thus, it has to take the longer path with a

![Fig. 11 Grain size variation at the center and periphery of the samples produced by FSBE.](a) Effect of plunging speed, and b effect of rotational speed
higher speed. Therefore, as discussed before, a higher strain is applied to the points at a higher distance from the tool axis.

To consider the total material flow pattern accompanied by the effects of process parameters, different points in consecutive distances of 1.15 mm are located along the diameter of the initial stock. The initial position of the points is shown in Fig. 13 from the top and front views. Then, the position of these points during the process is observed at different time intervals.

The effects of process parameters on the material flow pattern are shown in Figs. 14 and 15 from the top and front views. The general shapes of material flow patterns in all samples are similar to each other and include a conical helix pattern, but the speed of flowing points changes with changing the process parameters. As can be seen by increasing the plunging speed from 25 to 40 mm/min (Fig. 14a and b), the speed of material
penetration from the initial stock into the final wire increases. Furthermore, comparing the top views for two samples, one can be deduced that by increasing the plunging speed, the flowing points are rotated faster. Although a reverse result was expected, it seems that when the plunging speed is increased, the points are going faster toward the wire channel and consequently entered the deforming zone faster.

A similar effect can be observed when the rotational speed is reduced from 800 to 500 rpm (comparing Fig. 15a and b). In this case, the number of rotations for a point lowers before entering the sizing channel. Therefore, although the speed of entering the points from the initial channel into the sizing channel is the same (comparing the front views for two samples in Fig. 15), the number of rotations before entering the channel is reduced by decreasing the rotational speed from 800 to 500 rpm. This will lead the materials to experience a lower strain over the FSBE process.

5 Conclusions

In the present work, a primary 30-mm diameter brass shaft (as the initial stock) is formed to the 7-mm brass wire using friction stir back extrusion process. Additionally, a 3D coupled Eulerian-Lagrangian model is developed using the ABAQUS software to simulate the FSBE process of brass and verified by experiments. Then, the effects of process parameters of tool rotational and plunging speed on the temperature and strain distributions, microstructure, and material flow patterns are considered. The regions with the highest temperature and strain are identified, based on which the achieved experimental microstructure is justified. The results show that:

- The highest temperature and strain occur near the tool/workpiece interface but at a further distance from the tool axis. The higher rotational speed or lower plunging speed
causes an increase in the temperature and strain that the material experiences during the process.

- In the cross section of a produced FSBE sample (wire), the microstructure is more refined in the periphery rather than the center. This microstructural deviation is mainly affected by the strain rather than the temperature.
- However, when the process parameters are changed, the dominant factor in determining the product microstructure is the temperature rather than the strain. Therefore, a higher rotational to plunging speed ratio will result in a coarser microstructure.
- The flow pattern during the FSBE process is a conical helix (since the tool head is conical) and does not change significantly by the process parameters. The points at the further distance from the tool axis, along with an upward movement, experience an inward spiral movement which is amplified by a higher rotational speed. However, the material near the tool axis almost takes an upward movement and endures a significantly lower strain.

- The plunging speed is responsible for the wire production speed, while the rotational speed is responsible for the frictional heat and strain generation.

**Author contribution** All the authors have participated in the conception, design, analysis, and interpretation of the data as well as the writing, drafting, and revising of the article.

**Data availability** All of the required experimental data for reproduction of these findings are explained with details in the section “Experimental procedure.”

The general data for the reproduction of the proposed simulation model are described in the section “Model description”; however, some minor details cannot be shared at this time as the data also form part of an ongoing study.

**Declarations**

**Ethics approval** Since the study is performed on the metallic samples, there is no need for ethical approval; however, all the tests are done in
Imam Khomeini International University, in the metal forming, material processing, and SEM Labs under the control of trained experts. Additionally, the paper’s primary data is not published elsewhere.

Consent to participate All the authors declare that they have agreed to authorship, have read and approved the manuscript, and have given consent for submission and subsequent publication.

Competing interests The authors declare no competing interests.

References

1. Heidarzadeh A (2019) Tensile behavior, microstructure, and substructure of the friction stir welded 70/30 brass joints: RSM, EBSD, and TEM study. Arch Civ Mech Eng 19(1):137–146
2. Igelebgei EE, Alo OA, Adeolu AO, Daniyan IA (2017) Evaluation of mechanical and microstructural properties of Cu-Al–brass alloy produced from scrap copper and zinc metal through sand casting process. J Miner Mater Charact Eng 05(01):18–28
3. Heidarzadeh A, Laleh HM, Gerami H, Hosseinpour P, Shabestari MJ, Bahari R (2018) The origin of different microstructural and strengthening mechanisms of copper and brass in their dissimilar friction stir welded joint. Mater Sci Eng A 735(May):336–342
4. Heidarzadeh A, Barenji RV, Khalili V, Güleyüz G (2019) Optimizing the friction stir welding of the α/β brass plates to obtain the highest strength and elongation. Vacuum 159:152–160
5. Galai M et al (2017) α-Brass and (α + β) brass degradation processes in Azrou soil medium used in plumbing devices. Journal of Bio- and Tribo-Corrosion 3:30
6. Zhai Advisor Q, Yuan C Recycling metal chips from manufacturing industry through a combined hydrodynamic and electromagnetic separation approach Student Project Report. no. May, 2012.
7. Karadag HB, Bahtli T, Kara M (2016) The recycling of steel and brass chips to produce composite materials via cold pressing and sintering. Int J Eng Sci 5(5):1–6
8. Güleyüz G (Aug. 2020) Relationship between FSW parameters and hardness of the ferritic steel joints: modeling and optimization. Vacuum 178:109449
9. Yazdipour A, Heidarzadeh A (2016) Effect of friction stir welding on microstructure and mechanical properties of dissimilar Al 5083–H321 and 316L stainless steel alloy joints. J Alloys Compd 680:595–603
10. Akbari M, Asadi P (2020) Dissimilar friction stir lap welding of aluminum to brass: modeling of material mixing using coupled Eulerian– Lagrangian method with experimental verifications. Proc Inst Mech Eng L J Mater Des Appl 234(8):1117–1128
11. Mirzaei MH, Asadi P, Fazli A (2020) Effect of tool pin profile on microstructure of pure copper and dual-phase brass. Metallogr Microstruct Anal 8(5):73–45
12. Abu-Farha F (2012) A preliminary study on the feasibility of friction stir extrusion of magnesium chips. J Manuf Sci Eng Trans ASME 134(4):1–11
13. Baffari D, Bufà G, Campalessa D, Fratini L, Reynolds AP (2017) Process mechanics in friction stir extrusion of magnesium alloys chips through experiments and numerical simulation. J Manuf Process 29:41–49
14. Baffari D, Bufà G, Fratini L (2017) A numerical model for wire integrity prediction in friction stir extrusion of magnesium alloys. J Mater Process Technol 247:1–10
15. Zhang S, Frederick A, Wang Y, Eller M, McGinn P, Hu A, Feng Z (2019) Microstructure evolution and mechanical property characterization of 6063 aluminum alloy tubes processed with friction stir back extrusion. Jom 71(12):4436–4444
16. Behnagh RA et al (2016) Experimental analysis and microstructure modeling of friction stir extrusion of magnesium chips. J Manuf Sci Eng Trans ASME 138(4):1–11
17. Baffari D, Bufà G, Campalessa D, Fratini L, Reynolds AP (2017) Process mechanics in friction stir extrusion of magnesium alloys chips through experiments and numerical simulation. J Manuf Process 29:41–49
18. Meyghani B, Awang MB, Emamian SS, Mohd Nor MKB, Pedapati SR (2017) A comparison of different finite element methods in the thermal analysis of friction stir welding (FSW). Metals (Basel) 7:450
19. Assidi M, Fourment L, Guerdoux S, Nelson T (2010) Friction model for friction stir welding process simulation: calibrations from welding experiments. Int J Mach Tools Manuf 50(2):143–155
20. Ansari MA, Samanta A, Behnagh RA, Ding H (2019) An efficient coupled Eulerian-Lagrangian finite element model for friction stir processing. Int J Adv Manuf Technol 101(5–8):1495–1508
21. Dinaharan I, Zhang S, Chen G, Shi Q (Jan. 2020) Titanium particulate reinforced AZ31 magnesium matrix composites with improved ductility prepared using friction stir processing. Mater Sci Eng A 772:138793
22. Dinaharan I, Thirunavukkarasu R, Murugan N, Akinlabi ET (2019) Microstructure evolution and tensile behavior of dissimilar friction stir weld pure copper and dual-phase brass. Metallof Sci 30.01
23. Asadi P, Akbari M, Karimi-Nemeh H (2014) Simulation of friction stir welding and processing, in Advances in Friction-Stir Welding and Processing. In: Givi MKB, Asadi P Editors. Woodhead Publishing, pp 499–542
24. Tayebi P, Fazli A, Asadi P, Soltanpour M (2019) Formability analysis of dissimilar friction stir welded AA 6061 and AA 5083 blanks by SPIF process. CIRP J Manuf Sci Technol 25:50–68
25. Forsström A, Bossuyt S, Yagodzinszky Y, Tsuzaki K, Hämminen K (2019) Strain localization in copper canister FSW welds for spent nuclear fuel disposal. J Nucl Mater 523:347–359
26. Asadi P, Akbari M, Karimi-Nemeh H (2014) Simulation of friction stir welding and processing, in Advances in Friction-Stir Welding and Processing. In: Givi MKB, Asadi P Editors. Woodhead Publishing, pp 499–542
27. Nayebi P, Fazli A, Asadi P, Soltanpour M (2019) Formability analysis of dissimilar friction stir welded AA 6061 and AA 5083 blanks by SPIF process. CIRP J Manuf Sci Technol 25:50–68
28. Forsström A, Bossuyt S, Yagodzinszky Y, Tsuzaki K, Hämminen K (2019) Strain localization in copper canister FSW welds for spent nuclear fuel disposal. J Nucl Mater 523:347–359
29. Asadi P, Akbari M, Karimi-Nemeh H (2014) Microstructural simulation of friction stir welding using a cellular automaton method: a microstructure prediction of AZ91 magnesium alloy. Int J Mech Mater Eng 10(1):20
30. Fatemi L, Bufà G, Lo Monaco L (2010) Improved FE model for simulation of friction stir welding of different materials. Sci Technol Weld Join 15(3):199–207
31. Heidarzadeh A, Kazemi-Chooobi K, Hanifian H, Asadi P (2014) Microstructural evolution. In: Givi MKB, Asadi P (eds.) Advances in Friction-Stir Welding and Processing. Woodhead Publishing pp, 65–140
32. Li G et al (2019) Effect of self-reacting friction stir welding on microstructure and mechanical properties of Mg-Al-Zn alloy joints. J Mech Mater Eng 10(1):20
33. Zhang J et al (2020) Optimizing the mechanical properties of friction stir welded dissimilar joint of AM60 and AZ31 alloys by controlling deformation behavior. Mater Sci Eng A 773:138839

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.