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Investigating the effects of influential parameters on the process window during planetary rolling of the pure copper tube using simple rollers

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ABSTRACT

Influential parameters of the planetary rolling process for the production of copper pipes were initially defined as the reduction of area, feed (α) and inclination (β) angles, material entry rate or input rate, roller's shape and the rotational speed of the rollers. For evaluating the effects of these parameters, finite element method was selected as the best choice of continuum simulation procedures to reduce costs and save time. Extensive simulations revealed that for any specific reduction of area, feed and inclination angles, there should be a positive correlation between the rotational speed of the rollers and the material input rate for production of geometrically sound copper pipes. This finding brought the possibility of determining the suitable combinations of the influential variables for the production of geometrically sound pipe. These combinations can be summarized as the planetary rolling process windows at different area reductions, varying feed and inclination angles. These process windows show that by increasing the area reduction, the production range of the pipe becomes confined to the limited ranges.

Keywords: *Planetary rolling, Process window, Copper tube, Simple rollers.*

1. Introduction

Studying different pipe and tube production methods during the last decades has shown the key role of various rolling processes. In the first half of the 20th century, the technological development of the various rolling machines transformed the pipe and tube manufacturing industries in many ways. These evolutions have provided the possibility of producing dimensionally precise products with the specified qualities. Rolling a metal sheet strip into a circular cross-section using a special arrangement of successive rollers and then welding the bent sheet edges was historically the first pipe production method. This method known as welded seam pipe production is now widely used to manufacture vast dimension ranges of pipes. But for some applications presence of any kind of seam is prohibited, therefore, another method, seamless pipe production processes have been introduced [1]. Three-roll planetary rolling is one of the newest seamless pipe production methods. In this process, the cross section areas of blank or primary bars/tubes are reduced in one pass by passing through a set of especially cross angled rollers to produce the final tube shape [2]. Mentioned primary bars/tubes are short and massive cylindrical billets generally obtained through the casting or hot extrusion processes. This method is also known as Planetensh rägwalzwerk, PSW [3]. Figure 1 shows a schematics illustration of the rollers, mandrel, and tube in the planetary rolling process of tube. The rollers are positioned at an angle of 120° to each other around the central axis of the bar/tube. The two spatial intersection angles of the roller axes and the bar/tube axis were named as inclination angle (β) and feed angle (α), respectively, (Fig. 1). These angles play important roles in the planetary rolling process and their arrangements determine the failure or successful bar/tube production conditions.

Nakasuji et al. [4] reported that the feed angle (α) results in the development of forward force component to drive ahead the bar/tube through the rollers. Increasing this angle also increases the output speed of the pipe. The largest spatial angle formed between the rollers axes and bar/tube axis known as inclination angle (β) which can be positive or negative. This angle determines the overall arrangement of the devices and imposed area reduction due to the shape of rollers. The combined effects of these feed and inclination angles determine the ratios of rotational to axial velocity components and also the ratios of rotational to axial forces components exerted on the tube. Fomin et al. [5,6] have reported that the feeding angle is one of the most important parameters of this process to determine the amount of shear and longitudinal components of strain and the strain gradient amount in the cross-section of the rod/tube. The effects of rollers types, different inclination (β) and feeding (α) angles, and the amount of the cross-section area reduction on the depth and the appearance of surface spirals have been investigated in a series of reaches through laboratory experiments and finite element simulations [7-10]. It has been shown that secondary tube torsional deformation concentrates at the deformation zone, which can lead to the instability of rolling conditions. Therefore, it is recommended to change the design of the rollers in such a way that the twisting of the pipe is reduced. A remedy is to divide the concentrated deformation region into several sections consisting of torsion-free zones [11]. It has been shown that the imposed large deformations during planetary rolling of copper tubes caused increase of the tube temperature to 700°C which can affect the deformation behavior [12].

As with the other metal forming processes, friction plays an important role in the planetary rolling mill. The frictional effects can be incorporated into the upper bound formulation with the help of flow functions or incorporated into finite element formulation [13]. Considering the last method, the importance of friction and the surface quality of the rollers on the efficiency of this process was proved by simulations through ABAQUS software assuming rollers with rough grooves surface design [14]. Goncharuk et al. [15] investigated the dimensional accuracies of the beginning and end of the pipe, i.e. the uniformity of the thickness in the transverse section as well as in the longitudinal direction. This issue is important in the case of thick wall pipes where the difference between the diameter of the mandrel and the pipe is large. According to the literature, the most important parameters involved in this process are roller shape and roller design [3,16], roll face angle and gorge zone [4], inclination and feed angles [3,4], rotational and revolution speed of the rollers [11], initial diameter and amount of area reduction [17], roll surface condition [18], driving force [19], friction coefficient [13,14] and cooling process [20].

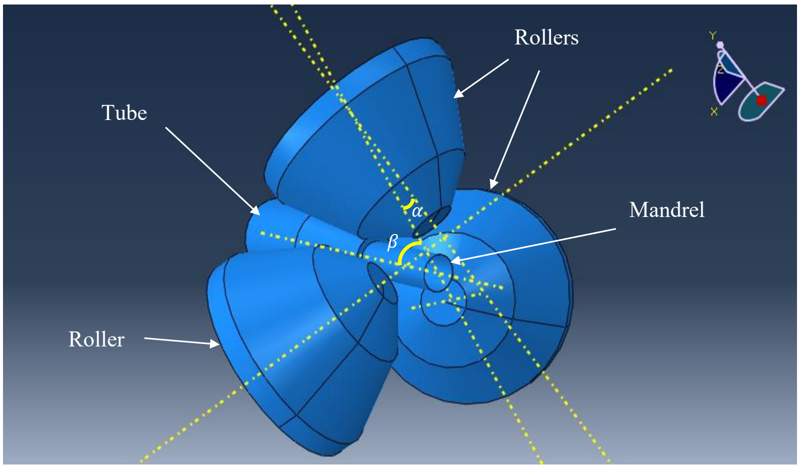

Fig. 1- Schematic of planetary rolling process showing the assembled components of the model with the 120° angle between rollers composed of tube, inclination angle (β), feed angle (α), and mandrel.

As clarified from the above brief reviews of articles related to the planetary rolling process, various parameters influence the success or failure of this process. Therefore, accessing the correct process parameters setting such as inclination angle (β), feeding angle(α), feeding speed of initial material input rate and its relation to the angular velocity of roll, the roll shape, etc. are very important for the production of sound copper tubes using the planetary rolling mill. Establishing required relations is tedious and expensive using the experimental method, while numerical simulations can be used with a logical expense. Therefore, in the present report as an example of such an attempt, it was tried to establish the relation between the feeding angle (α), the material input rate, and the angular velocity of simple shape rollers which can be represented as the process windows defining the conditions for the production of geometrically sound copper tubes.

2. Simulation procedures and assumptions

2.1 Material

The chemical composition of assumed TP2 Copper (compatible with the ASTM: C12200 standard [16]) for simulations of tube production by the planetary rolling mill is presented in Table. 1. The elastic constants and density of this copper are also shown in Table 2 [17]. The initial shape of the assumed material was in the form of a tube with an outer radius of 50 mm (outer diameter of 100 mm) and an inner radius of 25 mm (inner diameter of 50 mm).

2.2 Simulation procedures

For the simulation of copper tube deformation by the planetary rolling mill, ABAQUS version 2018 was used [23]. The initial copper tube deformations were simulated to produce three different final tubes. Arrangements of simple rollers and their dimensions are shown in Fig. 2 accompanying

Table 1- Chemical composition of copper TP2, wt-% [21]

Cu	Fe	Ni	S	P	Mn	other
99.90	0.005	0.005	0.004	0.039	0.002	0.045

Table 2- Mechanical properties of copper TP2[22]

Density (kg/m^3)	Young modulus (GPa)	Poisson's ratio
8913	117.3	0.33

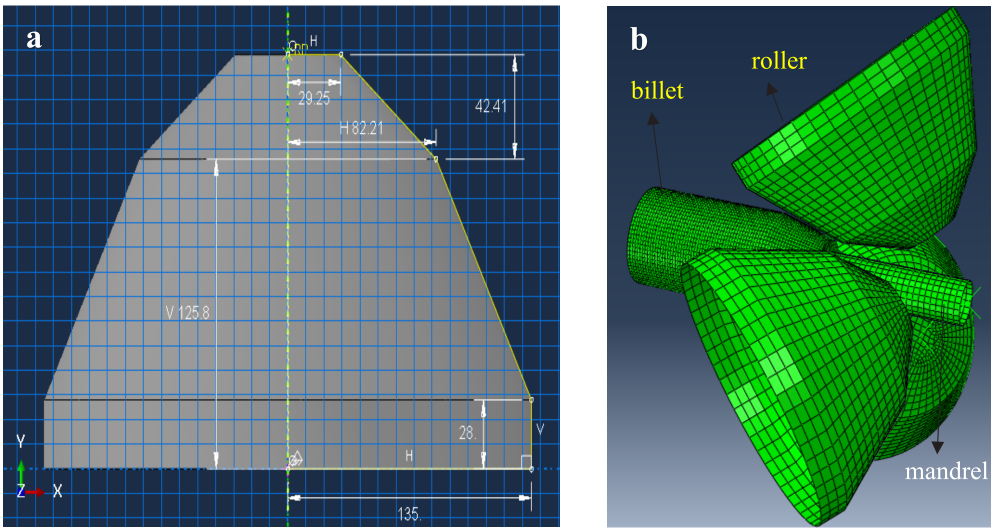

Fig. 2- Considered tooling in planetary rolling simulations a) detailed dimension of considered simple roller (mm), b) meshed and arrangements assembly of the simple rollers, pipe and mandrel.

mandrel with the diameter of 44 mm. All rollers and mandrels were assumed to be rigid objects, while the tube material was considered to be deformable. After mesh sensitivity analysis, the initial tube (billet) was discretized by C3D8R mesh with a size of 3×3 mm^2. During explicit analysis, the ratio of the kinetic to potential energy was kept as low as possible (0.1 or less). The behavior of TP2 copper during plastic deformation was assumed to obey Johnson-Cook's model with the suggested constants presented in Table 3 [22].

The surface-to-surface contact option accompanying the enforcing penalty constraint method was used to identify the contact between the rollers, billet, and mandrel. The penalty mode was considered due to the movement of the surfaces relative to each other, which is closer to reality [23]. The Coulomb frictional conditions were assumed to prevail between the rollers and the copper tube outer surfaces with a frictional coefficient of 0.6 from one side, and a frictional coefficient of 0.1 for the contacted mandrel with the tube inner surface from another side.

During a series of carried out simulations, the initial copper tube was deformed to three different area reductions of 44% (final tube of 39 mm outer diameter and 30 mm inner diameter), 62% (final tube of 34.5 mm outer diameter and 30 mm inner diameter), and 78% (final tube of 30 mm outer diameter and 30 mm inner diameter). Simulation attempts were carried out at the assumed feeding angles (α) of 9,12, and 15 degrees and fixed inclination angle (β) of 50°. The rotational speed of the rollers was assumed to vary between 10~50 Rad/Sec, while the assumed material input rates were changed between 80~350 mm/Sec. The simple shape of the rollers led to stable contact with the pipe and well pipe rotation. For simplicity of the simulations, the planetary rotation was not considered.

3. Results and discussion

The planetary rolling mill, as a complicated metal forming method, has complex interrelations between the effective parameters of the process. Therefore, the analysis of the parameter's effects on the outcome of the process should be carried out with care. In the present investigation by considering simple rollers of Fig. 2 accompanying the presence or absence of mandrel, the effects of the assumed variables (section 2.2) on the manufacturing of geometrically sound copper tubes were examined by examining the variations of strain distributions and deviation from the correct size of the final copper tube.

3.1 Effect of material input rate and the rotational speed of the rollers

During the preliminary phase of planetary rolling simulations, it was found that the material input rate is one of the main parameters that could be synchronized with step time (axial velocity) during simulations by ABAQUS. The material input flow rate into the planetary rolling must always be equal to the output flow rate for the success of the process. To check the effect of the material input rate variations by means of step time on the outcome of the process, several simulations were performed at the same frictional conditions, fixed rollers' shape and feeding angles (α) of 9° but different input rates of 83, 166 and 332 mm/Sec. The results of the simulations are shown in Fig. 3.

According to these results, at the cross-sectional reduction area of 62%, input rate of 166 mm/Sec., and roller rotational speed of 22 Rad./Sec., it was possible to produce geometrically sound pipe (Fig. 3c, d). Any deviation from the specific initial pipe entering rate, or in other words, deviation from the material input rate of 166 mm/Sec, leads to the production of a geometrically defective pipe. For example, at low material input rates for reduction area of 62%, simulations predicted that instead of producing a pipe with an outer radius of 34.5 mm, a tube with the outer radius of 39.5 mm could be produced due to the entering bulged tube caused by the predominance of rotational to axial forces. This led to an increase in the diameter of the produced pipe larger than expected (Fig. 3a, b). An increase in material input rate to 332 mm/Sec. at the same reduction area could lead to the production of a defective pipe with an outer radius of 34.5 mm but triangular cross-sectional area. Entering high amount of tube material is responsible for the extrusion type deformation and formation of the triangular shape (Fig. 3e, f). This behavior can be attributed to the inability of the rollers to rotate the excessive initial tube entering the roller gap and final buckling of the tube wall deformed to

Table 3- Constants of Johnson-Cook's model for copper TP2 [22]

$T_{melting}$ (°C)	$T_{transition}$ (°C)	A (MPa)	B (MPa)	C	n	m
1083	25	90	292	0.025	0.31	1.09

the triangular shape (Fig. 3e, f). A comparison of the equivalent strain distributions of Fig. 3a, Fig. 3c, and Fig. 3e clearly shows the effects of material input rates on the equivalent strain distributions. At the suitable material input rate of 166 mm/Sec, the equivalent strain is uniformly distributed around the deforming tube as shown in Fig. 3c. Reduction of the material input rate to 83 mm/Sec, (Fig. 3a), led to the non-uniform distribution of the equivalent strain due to the bulging and the predominance of rotational to axial forces. Otherwise, an increase in the material input rate to the 332 mm/Sec, (Fig. 3e), concentrates deformation at the roller contact point with the deforming tube and preventing the extension of deformation around the deforming pipe which led to triangular section shape of the outgoing tube.

The predicted simulation results of tube production at the billet input rate of 83 mm/ Sec. and 332 mm/ Sec using different rotational speeds of 11, 22, and 44 Rad./Sec. are shown in Fig. 4 and Fig. 5 respectively. For these material feeding rates as figures show, two rotational speeds of 11 and 44 Rad./Sec led to satisfactory conditions for the production of geometrically sound tubes. Any deviation from the established input rates and rotational speeds led to the geometrically defective final tube products which will result in the bulging of the entering tube wall and slightly triangular cross-sectional shape of deforming pipe because of the predominance of rotational to axial forces (Fig. 4c, d and Fig. 4e, f). The oversizing of deforming tube can be attributed to the excessive imposing rotational movements the rollers to rotate the initial tube entering the roller gap and predominance of the centrifugal force acting on the deforming tube over the axial forces which increase the diameter of the produced pipe larger than expected (Fig. 4e, f). Results of deviation from the input rate of 83 mm/Sec. at the rotational speed of 11Rad./Sec can be also explained based on the equivalent strain distributions predicted by the simulation of tube deformations as shown in Fig. 4a, Fig. 4c and Fig. 4e. Deviation from the mentioned values caused

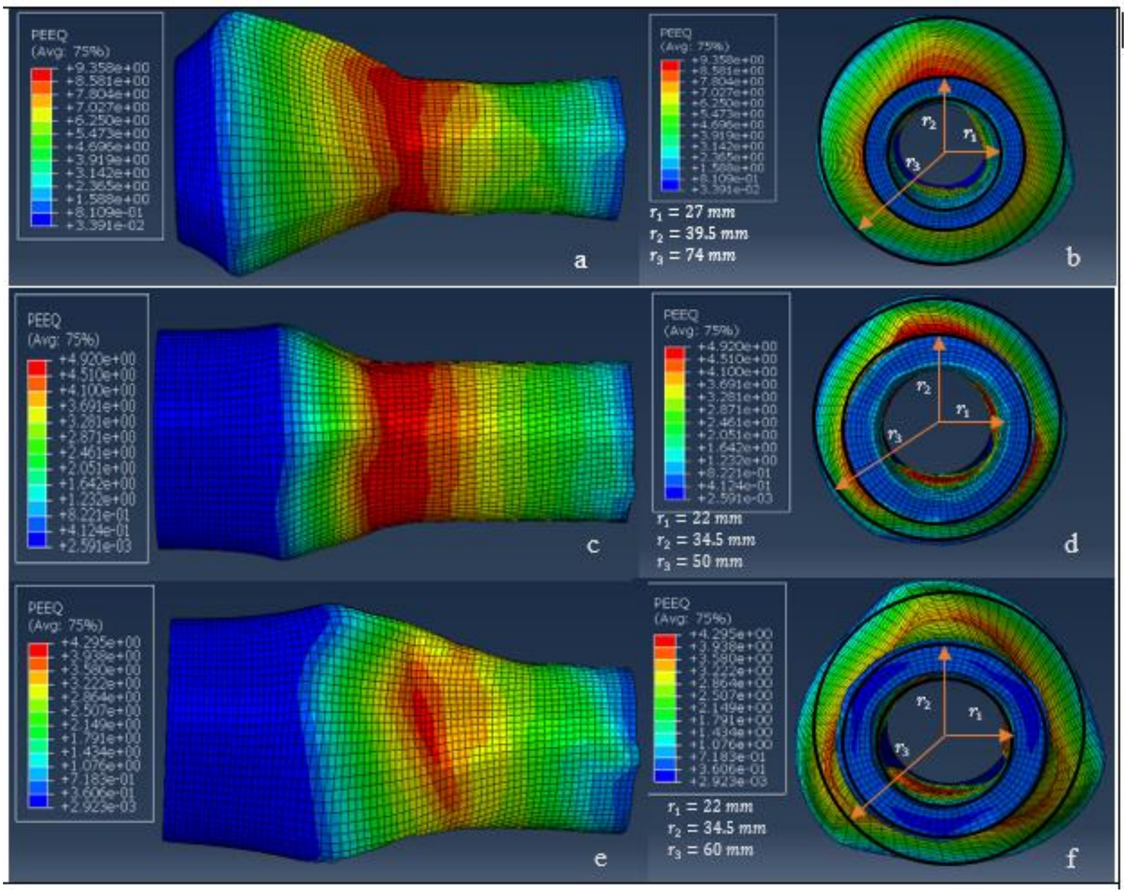

Fig. 3- The effect of material input rates on the outcome of the planetary rolling process of the copper tube at the constant rotational speed of 22 Rad./Sec., fixed feed angle (α) of 9° and the sectional reduction area of 62%:
a, b) 83 mm/Sec c, d) 166 mm/ Sec e, f) 332 mm/ Sec.

the developments of the non-uniform distribution of equivalent strain as shown in Fig. 4c and Fig. 4e due to the predominance of rotational to axial forces and bulging of the entering material at the entrance point of rollers. By increase of the rotational speed, the uniformity of strain distribution is disturbed to more non-uniformity and concentration of strain at the contact point of rollers and deforming tube. These could lead to the oversizing of the producing pipe diameter.

At the high material input of 332 mm/ Sec. and low rotational speeds of 11 and 22 Rad./Sec., simulations predicted the strain concentration at the contact point with the rollers, deforming tube to the triangular shape due to the extrusion type of deformation, bulging of material at the entrance point, and excessive non-uniformity of strain as shown in Fig. 5 a and Fig. 5c. Increase in the rotational speed to 44 Rad./Sec. improve the strain distribution that led to geometrically sound final tube. At the fixed material input rate of 166 mm/Sec., and constant frictional coefficient of μ=0.6, the effect of the rollers' rotational speed variations on the shape of final tube were examined by considering the rotational speed of rollers between 44, 22 and 11 Rad/Sec in order to show the consistency of results with previous simulation outcomes. Figure 6 shows a pictorial summary of the obtained results of simulations.

As it is observable, the results of simulations predicted that geometrically sound tube can be produced at the billet input rate of 166 mm/sec by using the rotation speed of 22 Rad./Sec. But any large deviation from the rotational speed of 22 Rad./Sec. caused unsatisfactory geometric shape of the final tube as demonstrated in the Fig. 6. Applying rotational speed of as high as of 44 Rad./Sec. at the considered material input rate of 166mm/Sec caused oversizing of the final tube due to the predominance of the rotational force over axial force (Fig. 6b) and excessive extension of the deformation zone as evident from the equivalent strain distribution of Fig. 6a. Too much reduction of the rotational speed toward values as

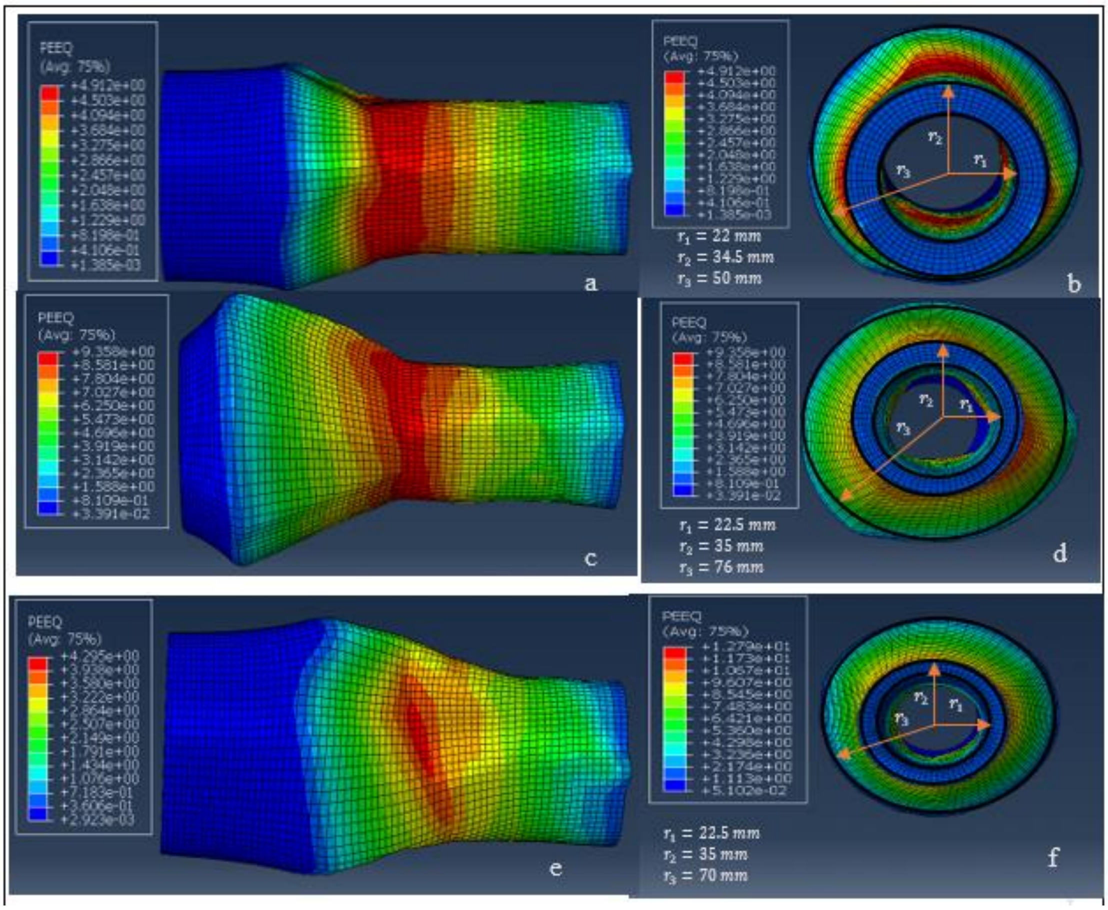

Fig. 4- Simulation results of planetary rolling process of the copper tube at a constant billet input rate of 83 mm/Sec., fixed feed angle of 9° and constant cross-sectional reduction area of 62% but different rotational speeds of: :
a, b)11 c, d) 22 e, f) 44 Rad/Sec.

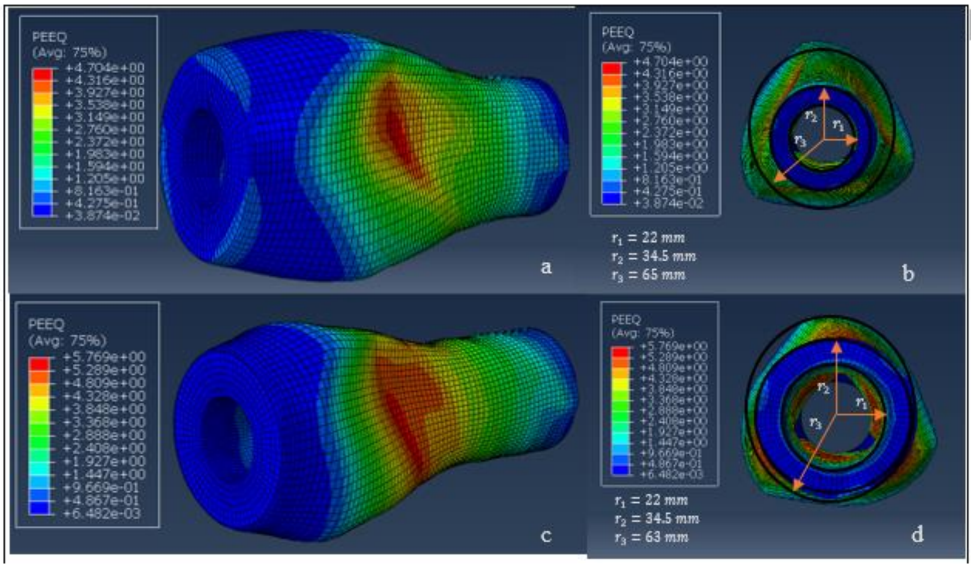

Fig. 5- Simulation results of planetary rolling process of the copper tube at constant input rate of 332 mm/Sec., fixed feed angle equal to 9°, and constant cross-sectional reduction area of 62% but different rotation speeds of:
a, b) 11 c, d) 22 e, f) 44 Rad/Sec.

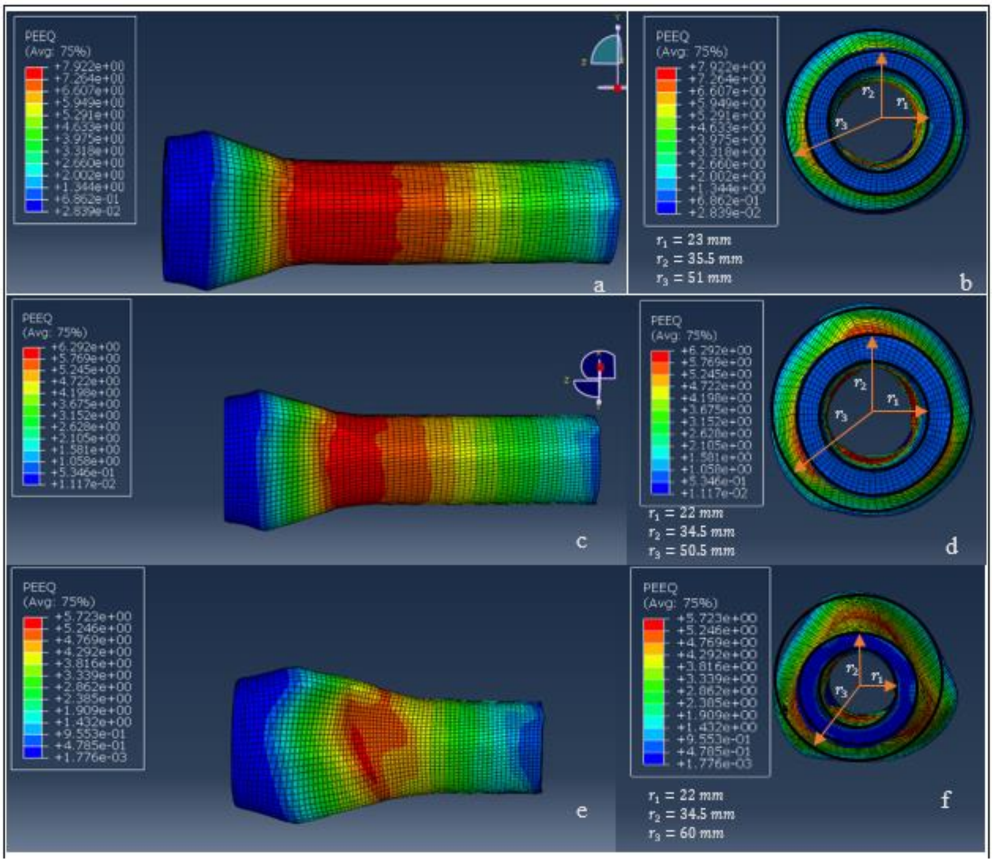

Fig. 6- Investigating the influence of the rotational speed of the rollers in the planetary rolling process of the copper tube at constant billet input rate of 166 mm/Sec., feed angle (α) of 9° and the cross-sectional reduction area of 62%:
a, b) 44 c, d) 22 e, f) 11 Rad./Sec.

low as of 11 Rad./Sec. at the fixed material input rate led to the concentration of the deformation at the contact area between roller and tube due to the extrusion type deformation and entering of excessive material at the rollers gap which directed toward the formation of triangular shape of tube. These happening can be explained by noticing to these facts that by increasing the rotational speed of the rollers, both rotational and axial speeds increased due to the combination effects of the feeding angle (α), the inclination angle (β), and the geometry of rollers [11]. The rotational speed of the pipe increases with the increase of the rotation speed of the rollers because of the imposed shearing and axial forces by rollers as shown in Table 4. As mentioned in this table, increase in the rotational speed from the 22 Rad./Sec. to 50 Rad./Sec. increased shear stresses from the 334 MPa to the 371 MPa, and axial stresses from the 855 MPa to the 1040 MPa respectively. These stress changes can influence the pattern of plastic deformation due to the increased strain components. Therefore, it was predicted that the material input rate should be compatible with the rotational speed of rollers for every reduction of area. In another word, there should be some correlation between the material input rate and the rotational speed of rollers.

Hence a series of simulations at the same considered boundary conditions but different reductions of areas were carried out to investigate the existence of the probable relation between the material input and rotational speed of rollers. The results of carried out simulations are presented in Fig. 7. According to this figure, it is possible to express a ratio between the rotational speeds of rollers and material input rates. As can be seen, the rotation speed of the rollers linearly increases with the increase of area reduction and input rate. For example, at the reduction area of 44%, ratios of the material input rate to the rotational speed varied from 82/8 Rad/mm to 332/30 Rad/mm by changing the material input rate from 82 mm/Sec to 332 mm/Sec. At the reduction area of 78%, ratios of input to rotational rate varied from 82/16 Rad/mm to 332/70 Rad/mm by changing the material input rate from 82 mm/Sec to 332 mm/Sec. Therefore, from these linear variations, it can be deduced that there should be some relation between the material input rate and the material output rate. The outcomes of carried out simulations as the changes in the ratio of output to input rates at different reductions of areas for the constant feeding angle (α) of 9° are shown in Table 5.

Table 4- Relation between rotation speed, shear stress and axial forces at reduction area of 62%, feeding angle (α) of 9°, inclination angle (β) of 50° and input rate of 166 mm/Sec.

	Rotation speed of rollers (Rad/Sec)			
	22	**30**	**40**	**50**
Shear stress (MPa)	**334**	**344**	**352**	**371**
Axial stress (MPa)	**855**	**909**	**945**	**1040**

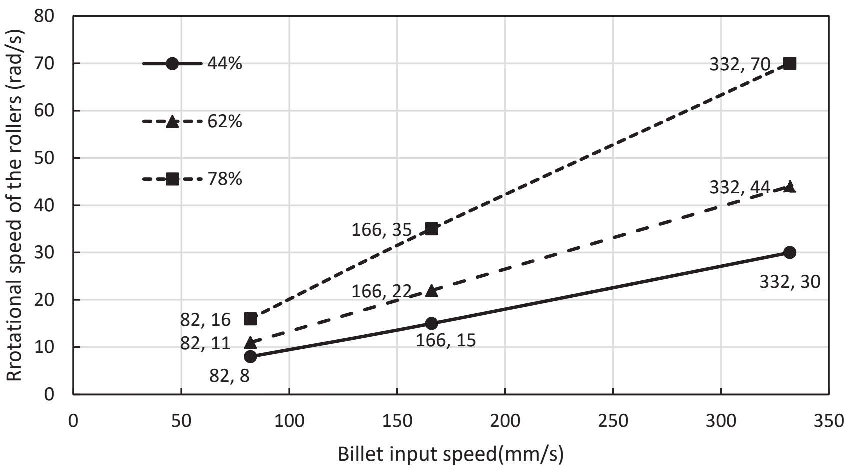

Fig. 7- Relation between billet input rate and rotational speed of rollers at feed angle of 9° and reduction areas of 44%, 62%, 78%.

3.2 Feeding angle (α) and process window

The relations between reduction of area, material input rate, and rotation velocity were presented. The feeding angle (α) is a parameter that controls both angular and axial velocity at constant material input rate and fixed inclination angle (β). From these results it is possible to extract and present the suitable production conditions of the geometrically sound tubes based on the considered geometrical criteria in a pictorial manner. In this way process windows are introduced which demonstrate the relations between the aforementioned parameters for production of the geometrically sound tube using simple shape rollers considering the variation of rollers' rotational speed, material input rates, and feeding angles (α) at a constant inclination angle (β) of 50°. In Fig. 8, Fig. 9, and Fig. 10 the predicted process windows through many FE simulations considering different reduction of areas of 44, 62, and 78 percent are shown for various feeding angles of 9°, 12°, and 15°, respectively.

As shown in the Fig. 8, the limiting boundaries can be divided into four regions: left, right, below and above the process window regions. The left limiting side of the drawn process window restricts due to the low output production. This limiting boundary is considered to be related to the deforming material characteristics. The right limiting side of the process window (high output production) is possibly restricted by supplying required forces and torques. The below limiting boundary of the process window, as demonstrated in the Fig. 8, can be connected to the incompatibility of the rotational speed of rollers and the material input rate which led to the inability of the rollers to exert the required shearing force to rotate the tube. Therefore, material is extruded among the rollers which lead to the triangular shape of the emerging tube section. The above limiting boundary of the process window, as demonstrated in the Fig. 8, can be related to the incompatibility of the rotational speed of rollers and the material input rate which led to excessive rotation and bulging of tube. Therefore, the bulged material will stop deformation behind the rollers and even the produced tube will have oversize outer diameter.

Generally, comparison of Figs. 8, 9 and 10 shows that at a constant feeding angle (α), increase of area reduction clearly causes the contraction of the process window which means tightening of the production condition of manufacturing of sound tube. Also, from this comparison, it can be deduced that besides the slightly reduction of the process window, they were moved to high ranges of the required material rotation rates by increase of the feeding angle from 9° to 15°. For example, while for the feeding angle of 9°, the acceptable minimum and maximum rotational rate variations range at constant area reduction of 44%, were 8 Rad./Sec. and 65 Rad./Sec. respectively, increase of the feeding angle to 15° caused the transfer of the minimum and maximum rotational rates to 10 Rad./Sec. and 75 Rad./Sec. correspondingly. These results clearly indicate to this fact that both increase in the feeding angle (α) and area reduction lead to the contraction of the process window which means the necessities of the close control of the aforementioned parameters.

The introduction of process windows can play important rule in the designing manufacturing process of various metallic tubes using planetary rolling mills. For examination of offered process windows and effects of variables by experimental trial and errors, expensive small size laboratory instruments or full scale industrial plant can be used. The first one is not accessible and the second one will be impractical. Therefore, such processing windows can be practically predicted even by using simple rollers during FEM simulations for up to 78% pipe area reduction. For investigation of predicted simulation results worth, using the same applied simulation procedures, the 92% area reduction of copper tube using grooved rollers of Bahoner Copper Company of Kerman was also simulated. Simulation results showed that the geometrically sound pipe can be produced at the rotational rollers speed of 11.52 Rad./Sec. and output speed of 170 mm/s. In reality at the same reduction of area and rotational roller speed, the output speed of the pipe is equal to 10 m/min or 166 mm/sec. Therefore, there is good agreements between the experimental and simulation results and it can be anticipated that such suggested process windows can help to the designing of forming process.

Table 5- The relation between the percentage of area reduction and velocity rate at feed angle of 9°.

Area reduction %	**44**	**62**	**78**
The ratio of output to input rate	**1.5**	**2**	**2.8**

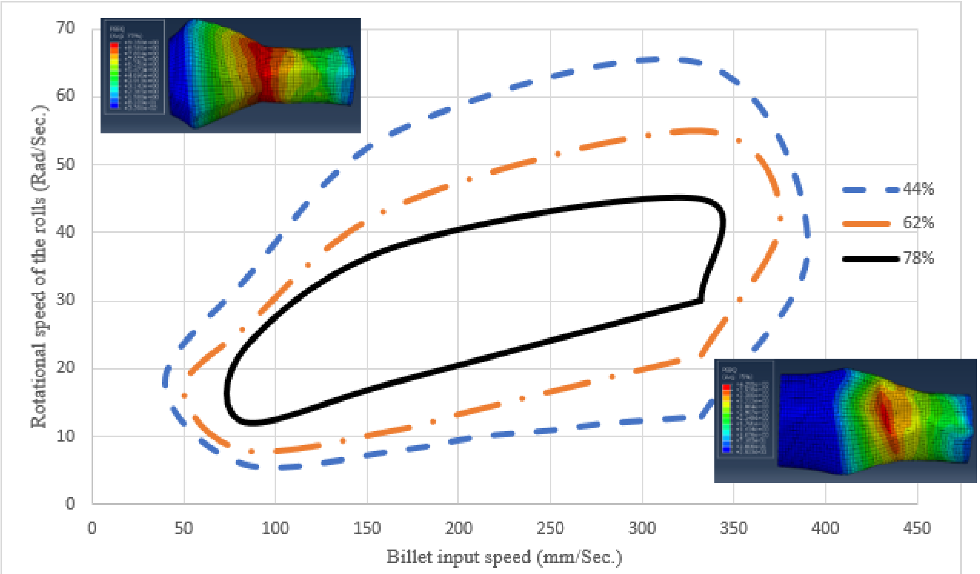

Fig. 8- Process window for feed angle (α) of 9° at different area reductions.

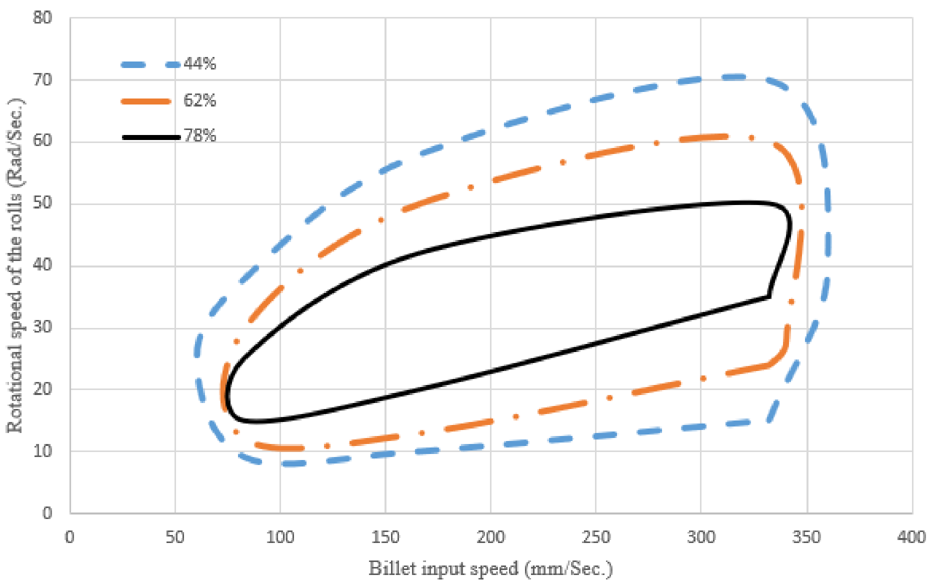

Fig. 9- Process window in feed angle 12° (α) at different area reduction.

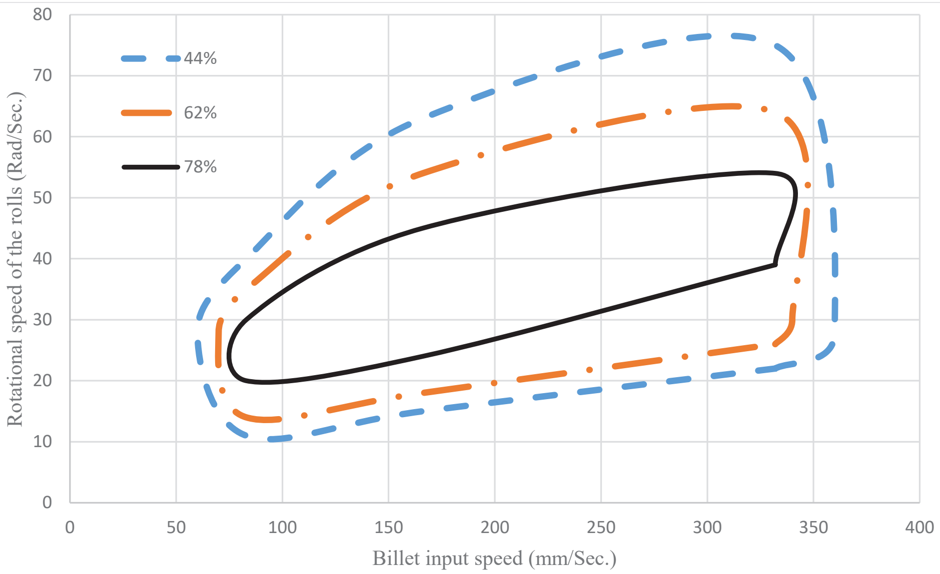

Fig. 10- Process window in feed angle 15° (α) at different area reduction.

4. Conclusion

In this study, the simulation of planetary rolling process for production of copper tubes was successfully carried out using finite element method. The outcome of simulations can be summarized as:

1- The material input rate should be selected based on the total area reduction and the rollers rotational speed during the process, so that with the increase of the area reduction both the material input rate and the rotation speed of the rollers should also increase. Otherwise rolling and production of the tube will not possible.

2- By increase of the area reduction, the ratio of the output speed to the input speed of the pipe increases during rolling.

3- The rotation speed of rollers should be increased by increase of the feed angle (α) at constant inclination angle (β).

4- The simulation results were presented as the process windows for the three different feed angles (α) considering fixed condition for other parameters. This process windows show the safe working area for production of geometrically sound copper tubes. The safe production range or process window of the copper tube become smaller by the increase of area reduction. Increase in the feed angles (α) lead to the restriction of the upper and lower limits of the process window.

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