Effect of process parameters on final geometry and quality in hot tube spinning process

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Abstract. Spinning is one of the oldest metal forming processes that produce rotationally axisymmetric and seamless final products by using plates or tubes [1]. Preform can be shaped via rollers, hot or cold and it has a big advantage in terms of manufacturing complex geometries [2]. It is used in many different industries around the world. However, the wall thickness of the output (final geometry) might be uneven or the roller path might be different than expected. It is clear that all of those results have a negative impact on the quality of the process, as they make it difficult to obtain the desired final geometry. Within the context of this study, the cylindrical tube will be used in the hot spinning metal forming process. It will be investigated how the reduction ratio, the roller geometry and the initial temperature of the preform affect wall thickness of the final geometry with the help of finite element analysis software.

Introduction

It is commonly acknowledged that the finite element method is an effective tool for metal forming analysis since with this technique it is possible to determine the fields of displacements, stresses, and strains, as well as the distributions of loads and pressures, at every stage of the deformation and this allows the analyst to optimize the forming parameters by adjusting certain process parameters [1] such as the geometry of the dies, process temperature, friction coefficient and along with others. In this paper, the authors work with FORGE®, which is a software that can perform hot and cold forming processes.

In recent years, hot spinning has been emphasized since the process force is relatively lower, although the formability of the process is still higher to produce complex part [3]. It can be perform as either hot or cold (room temperature) process, yet hot tube spinning process looks more complicated due to the fact of it has different deformations ways at the same time in the deformation zones, such as bending, shear, thickening and thinning, compression and elongation [3]. Although hot tube spinning, mentioned in this paper, is a different process, in literature, tube spinning and flow forming are used synonymously [4], and this might cause misleading in the context of this study. In tube spinning (flow forming) process, a tubular preform rotates with a mandrel and deforms by rollers [5] while hot tube spinning, in the presented study, does not require any mandrel and is conducted at elevated temperature. A number of researchers have carried out experimental and numerical studies regarding the impact of different parameters on the spinning process. In this paper, temperature, roller geometry and, reduction ratio, known as the percentage of deformation in the thickness direction [6], will be analyzed to understand how to optimize the hot tube spinning process with the numerical outputs drawn from commercial software FORGE®.

Building of the Finite Element Model

Two different preform initial temperatures, three different reduction ratios and two different forming geometries were determined as analysis parameters as in the Table 1 below.

Table 1. Finite element analysis parameters

Temperature	Reduction ratio	Forming Roller
1100 °C (T1100)	2 mm (R2)	R15 (F1)
750 °C (T750)	4 mm (R4)	R27.5 (F2)
	6 mm (R6)	

For the finite element analysis 12 sets with different combinations have been created in FORGE® to understand the effect of the temperature, reduction ratio and geometry of the forming roller, as can be seen in the Table 2.

Table 2. All setups used for the finite element analysis

Temperature °C	Reduction ratio (mm)	Forming Roller
T1100	R2	F1
T1100	R4	F1
T1100	R6	F1
T1100	R2	F2
T1100	R4	F2
T1100	R6	F2
T750	R2	F1
T750	R4	F1
T750	R6	F1
T750	R2	F2
T750	R4	F2
T750	R6	F2

The CAD model of the simulation contains two forming rollers, one preform (workpiece) and one headstock.

Rollers

Rollers in many different forms are used in practice. In this study, the effect of the radius on the roller geometry shown in Fig. 1 on the process outputs (thickness and force) will be examined.

The rollers were chosen as rigid bodies in the analysis, and they have fine meshes locally since the radius of the rollers has the main role in forming. The roller geometry has been analyzed in terms of their two different radii, which are 15.0 mm (F1) and 27.5 mm (F2), shown in Fig. 2a and Fig. 2b, respectively.

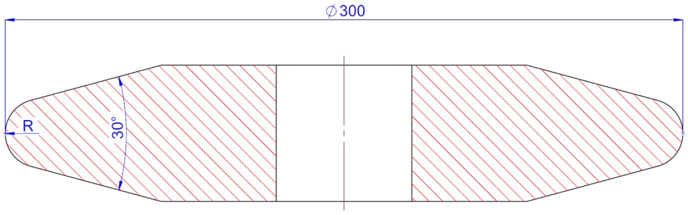
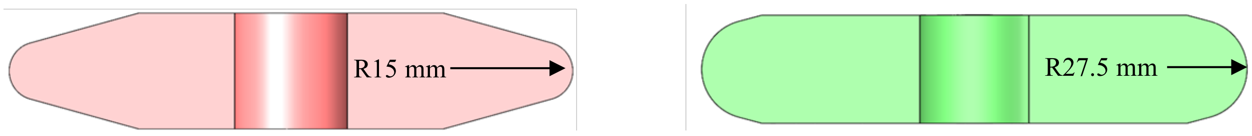


Fig. 1. Forming roller geometry

The generic press is assigned to the rollers. When using the "generic press" model, the motion characteristics will be a function of the rotational movements around two distinct axes combined with a translational motion [7].



a) *b)*

Fig. 2. Different forming roller geometries used a) F1: radius for 15 mm for b) F2: radius for 27.5 mm

Preform

The preform material is AISI 4140 (42CrMo4, DIN 1.7225) whose chemical composition is shown in the Table 3 below:

Table 3. AISI 4140 material properties

Properties	**Metric**
Tensile Strength	655 [MPa]
Yield Strength	415 [MPa]
Elastic Modulus	190-210 [GPa]
Poisson’s Ratio	0.27-0.30
Density	7.85 [g/cm^3]

The dimensions of the preform were chosen from the DIN 2448 standard for seamless carbon steel pipes and tubes whose outer diameter is 114.30 mm and wall thickness is 5 mm, as shown in Fig. 3 below. If the face of the preform in contact with the HS is considered as the zero point, the distance defines the axial distance of a point on the preform to zero point. The length of the preform is 300 mm. However, forming will start at distance 100 mm. In other words forming length is 200 mm, as shown in Fig. 3.

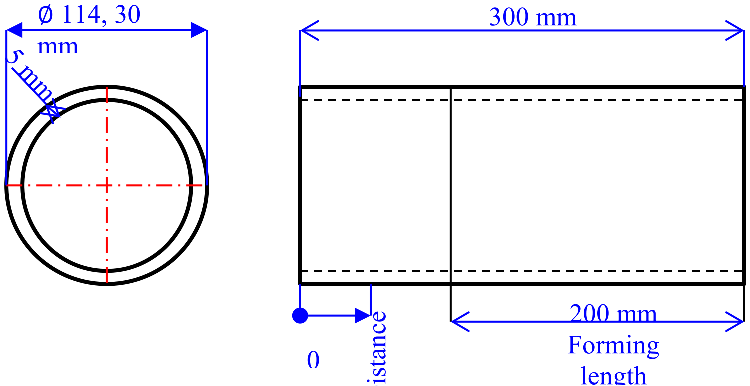


Fig. 3. Preform geometry

In this study, the FORGE® material library was used to define material properties. The Hansel-Spittel law applies to describe the viscoplastic behavior of the material. It is temperature-dependent and takes strain hardening or softening phenomena into account. It also takes the strain rate of the material into account as it is represented in Eq. 1:

$$\sigma = Ae^{m_1T}T^{m_9}\varepsilon^{m_2}e^{\frac{m_4}{\varepsilon}}(1+\varepsilon)^{m_5T}e^{m_7\varepsilon}\dot{\varepsilon}^{m_3}\dot{\varepsilon}^{m_8T} \quad (1)$$

where σ is stress, ε is strain, $\dot{\varepsilon}$ is strain rate, T is the temperature given in Celsius m1 and m9 define the material's sensitivity to temperature, m5 term coupling temperature and strain, m8 term coupling temperature and strain rate, m2, m4, and m7 define the material's sensitivity to strain, m3 depends on the material's sensitivity to the strain rate.

For the preform temperature (temperature parameter) , a gradient transition is preferred instead of a sharp change from 1100 °C and 750 °C to room temperature, as shown in Fig. 4 below.

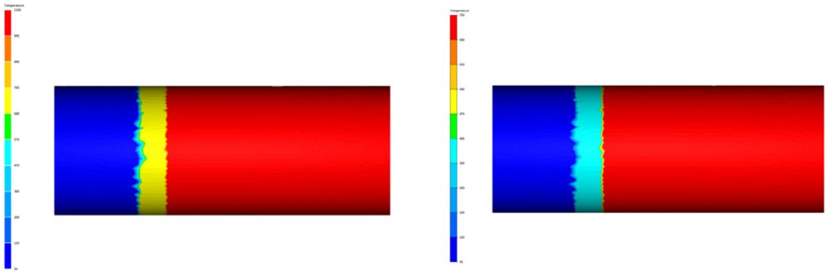


Fig. 4. Preform temperature distribution in finite element analysis

As in the actual hot tube spinning process, the preform has one degrees of freedom, which is the rotational movement around the z-axis. The forming rollers can move along the z-axis and y-axis while they are also rotating around the z-axis as shown in Fig. 5. Coulomb limited Tresca friction model which is considered the frictional shear stress at the part-tool interface is a fraction of the material's maximum shear [7] was used between the rollers and the preform, and water-graphite was selected as the lubricant. The angular speed of the preform is 200 rpm.

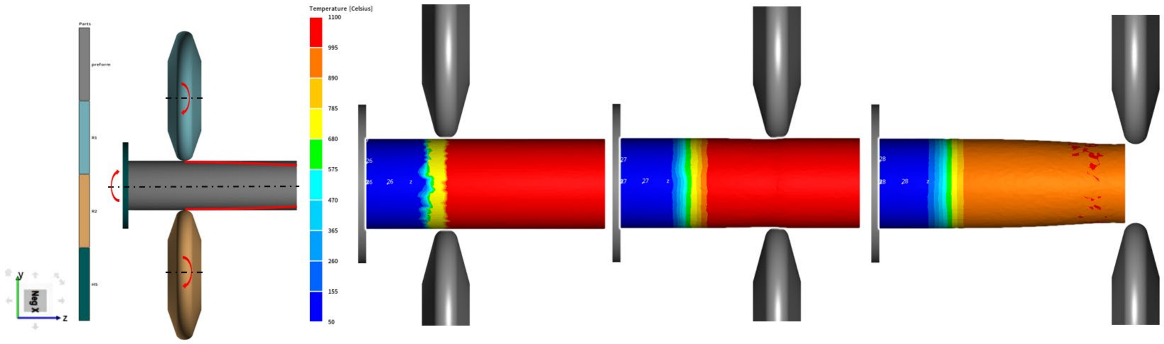


Fig. 5. Coordinate system of the model and Roller Path

As a default element type of FORGE® P1, the tetrahedron element type is used. To decrease the computational time mesh refinement was applied on the preform and the forming rollers. The shape of the edge of the rollers, which contacts the preform in real processes, was created, and these areas are meshed finely regenerating meshes shown in Fig. 6 below.

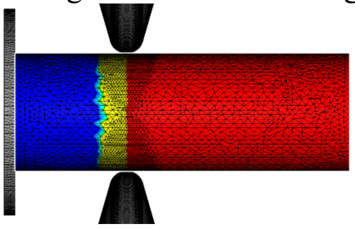


Fig. 6. Preform initial meshing

To determine the roller velocity in the direction of the y and z axis, circular interpolation was used. After the hot spinning process step design is made, the roller movements are transferred to the CNC controller via the G code (RS-274) structure. Since the center of rotation of the rollers follows an arc-shaped direction, G02 or G03 circular interpolation is used [7,8]. This code structure defines the starting point, end point, radius and constant tangential velocity of the arc. In circular interpolation, the simultaneous motion of two axes generates a circular arc at a constant tangential velocity or feed rate V_0. The axial velocities satisfy the Eq. 2 and Eq. 3 below:

$$V_x(t) = V_0 \sin\theta\,(t) \tag{2}$$

$$V_y(t) = V_0 \cos\theta\,(t) \tag{3}$$

where

$\theta(t) = \left(\frac{V_0}{R}\right) t$ and R is the radius of the circular arc.

For the different reduction ratios (2 mm, 4 mm, and 6 mm) which will be used in the simulation, axial velocities were determined with a constant tangential velocity of 1600 mm/min (26.67 mm/sec) shown in Fig. 7. After all velocity values are drawn they are added to the FORGE® press definition.

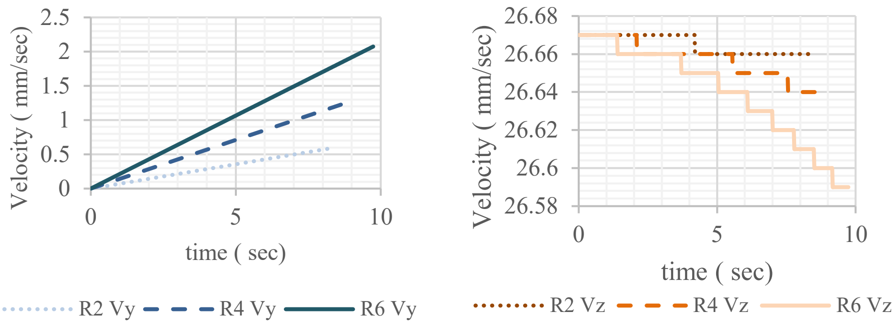


Fig. 7. Roller velocity in the direction of y and z

Results and Discussion

The simulation analysis is performed to obtain any relationship between wall thickness after the hot spinning process and the parameters, which are temperature, roller geometry and the reduction ratio. With the context of this purpose, the impact of these parameters will be interpreted. Before evaluating the effect of the parameters on the wall thickness, it ought to be noted that temperature has a major influence on the process force in the direction of the y-axis. When temperature increases, the related force decreases by more than half, as can be seen in Fig. 8.

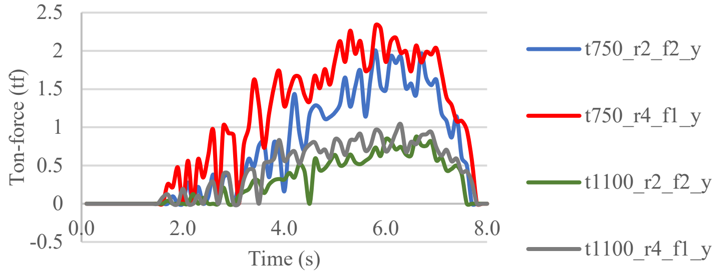


Fig. 8. Effect of the temperature on the roller force in direction of y-axis

While roller geometry has no effect on the process force shown in Fig. 9, the reduction ratio affects the force by 15-30 %, as shown in Fig. 10.

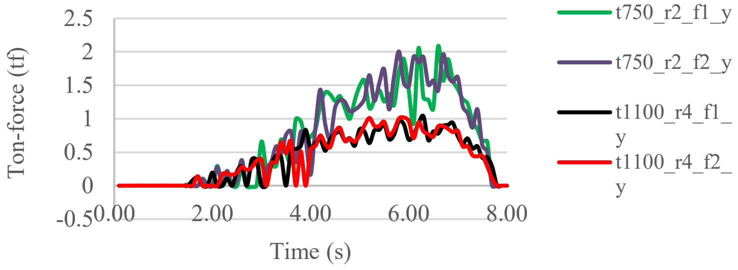


Fig. 9. Effect of the roller geometry on the roller force in direction of y-axis

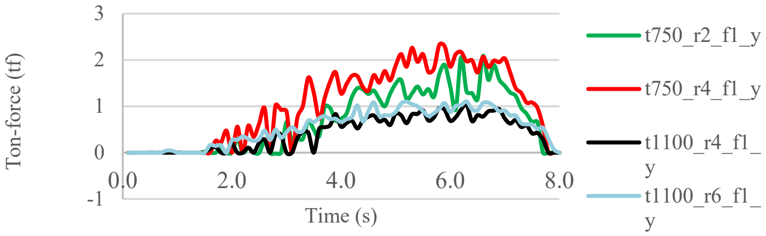


Fig. 10. Effect of the reduction ratio on the roller force in the direction of the y-axis

Effect of Parameters on Wall Thickness

1. Temperature

In order to understand the effect of temperature, analyzes with the same reduction ratio and cylinder geometry yet different temperature values were taken as it is shown in Fig. 11.

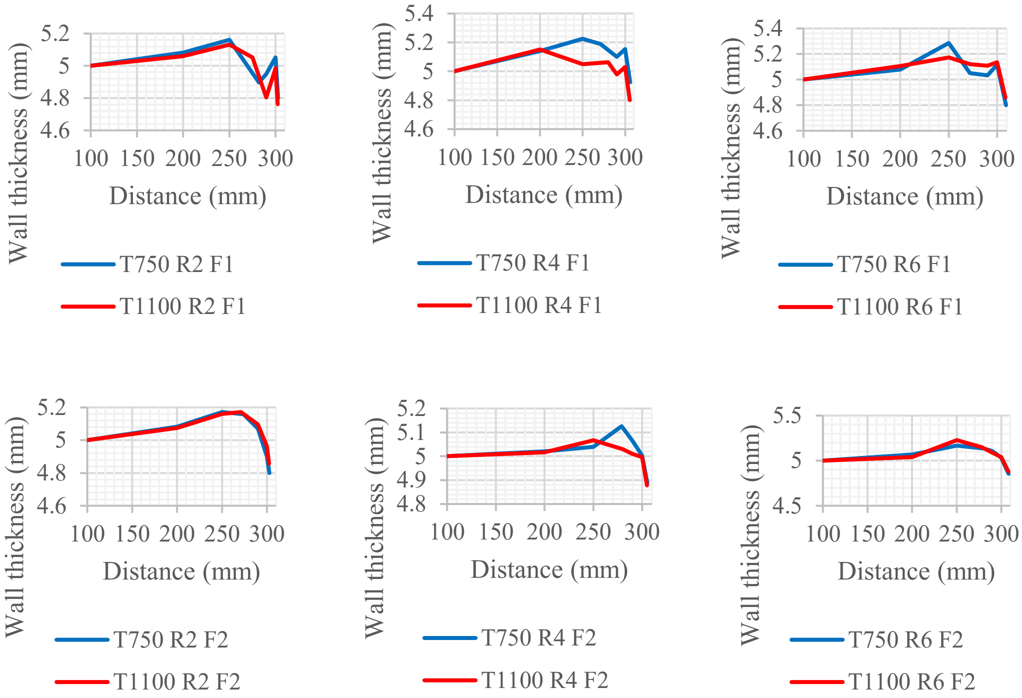


Fig. 11. Effect of the temperature on the wall thickness

When the wall thickness is examined in Fig. 11, -it is observed that it increases up to a certain point and then becomes thinner. This is valid for all analysis combinations. Accordingly, it can be concluded that changing the reduction ratio, temperature and roller geometry changes the thickening rate but does not change the effective thickness orientation.

If the analysis pairs using the F1 roller, where only the preform temperature was changed, were evaluated, it was seen that increasing the initial temperature reduced the wall thickness thickening. No similar results were observed in the analyses performed with the F2 roller.

2. Reduction Ratio

In order to understand the effect of reduction ratio, analyzes with the same temperature and cylinder geometry yet different reduction ratios were taken as in Fig. 12.

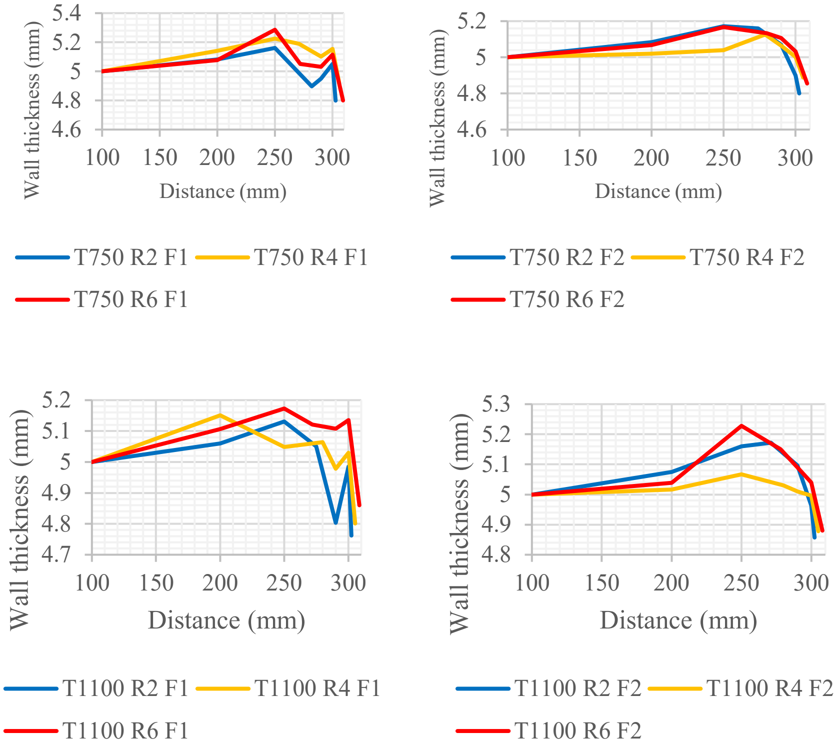


Fig. 12. Influence of reduction ratio on the wall thickness

When the analysis pairs where only the reduction ratio changed were evaluated as shown in Fig. 12, it was seen that the thickening was greatest in cases where the reduction ratio was highest. In addition to thickening, it was observed that the external form of the formed part was different from the path followed by the roller, and deviations occurred, as represented in Fig. 13. As the reduction ratio increases, this amount of deviation also increases. Deviation from ideal geometry affects the dimensional tolerances of the final part. Considering that dimensional tolerances are a quality parameter, it may not be possible to meet quality requirements in processes with high reduction rates. To meet the dimensional quality requirements, it is recommended that a multi-step process be preferred and the reduction ratios of the final steps be smaller.

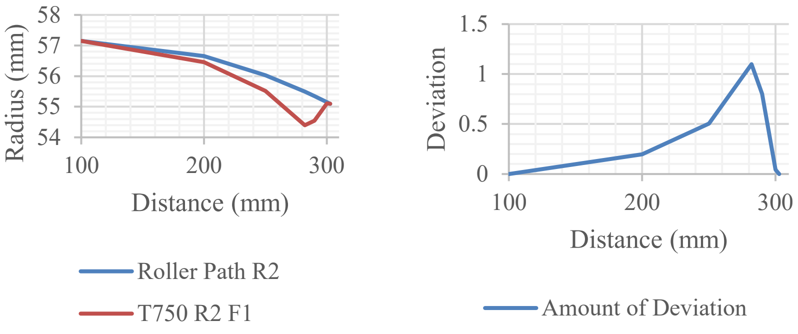


Fig. 13. Amount of the deviation for T750 R2 F1

3. Roller Geometry

In order to understand the effect of roller geometry, analyzes with the same temperature and reduction ratio yet different roller geometry were taken, as shown in Fig. 14. When the pairs of analyzes where only the roller geometry changed were evaluated, as shown in Fig. 14. It has been observed that the roller geometry changes the thickening character at the tip. While the thickness increased again at some point when roller F1 was used, it decreased steadily when roller F2 was used.

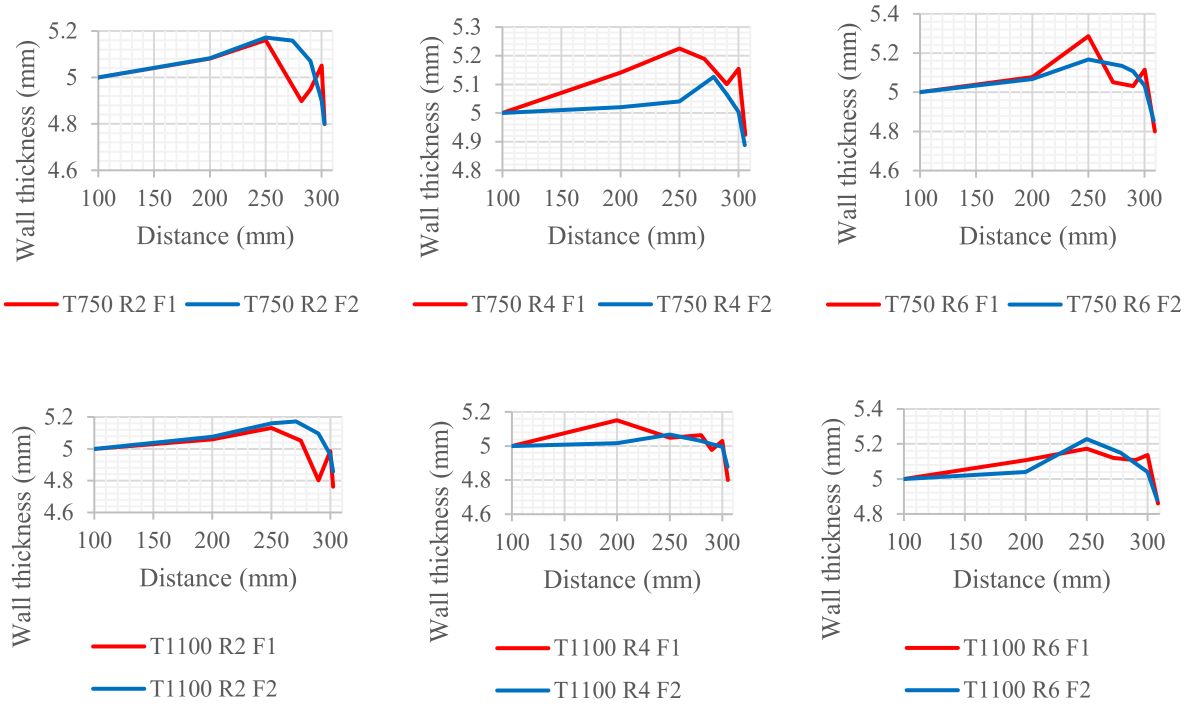


Fig. 14. Influence of roller geometry on the wall thickness

Conclusion

In this study, a well-founded finite element model was established in FORGE® to make a prediction regarding the effect of the temperature, reduction ratio and roller geometry on the wall thickness. As an auxiliary finding, the impacts of these parameters were also observed on the force in the y-axis. According to the analysis results, it was observed that as the temperature increased, the increase in wall thickness decreased, and the force in the y-axis direction decreased by almost half. Another observed parameter, the reduction ratio, has a directly proportional effect on the wall thickness. In other words, the thickening was greatest in cases where the reduction ratio was highest. As the reduction ratio increases, the amount of deviation from the ideal geometry also increases, the quality of the desired geometry is not achieved. It was observed that the roller geometry changed the thickening character in the end region of the part. If a roller with a larger forming zone radius is used, the thickness of the end zone gradually decreases.

It would be very worthwhile to test the results of the analysis with the real process. It is planned that this will definitely be done in future studies as an extended version of this research.

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