INVESTIGATION OF THE CROSS WEDGE ROLLING PROCESS*

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Abstract
Cross wedge rolling is a complex and widely applied process to produce stepped shafts and preforms for the forging industry. The design of process tools represents a considerable challenge, and their geometric parameters control the tendency to generate defects. In this work, numerical simulation was applied to expose the specificities of the cross-wedge rolling tool designed. Finite element analysis was employed to define the optimum parameters for generating an axisymmetric preform for the forging process. In addition, the effects of the tool geometry parameters on product qualities was extensively discussed..
Keywords: Cross wedge rolling; Finite element analysis; Tool Design.

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1 INTRODUCTION

Cross wedge rolling (CWR) is a mechanical forming process in which wedge-shaped tools deform a generatrix into an axisymmetric shape. The application of this technology has grown continuously, mainly to produce shafts for different industrial sectors [1]. In addition, the process is widely employed to preform complex geometry, allowing the material optimization and reducing the wear in the forging dies [2].
Numerical modeling of cross-wedge rolling processes has been expanding the application areas of the technology and developing new solutions to make manufacturing processes more efficient. Thus, this work aims to expose the specificities of the design of cross-wedge rolling tools from the numerical investigation of the process to generate an axisymmetric preform for the forging process.

2 CROSS WEDGE ROLLING TOOL DESIGN

Cross-wedge rolling is an efficient process for producing axisymmetrical and multi-diameter revolution parts such as drive shafts, hydraulic valves, spindles, worms, etc. Parts with diameters up to and lengths up to and including can be manufactured. The process is commonly carried out from cylindrical dies, but is not limited to these geometries. Square or hexagonal cross-section dies and tubes can also be machined. In the case of tubular generatrix, the thickness of the part can be changed as a result of CWR [3]. Figure 1 shows some examples of products produced by this technology [4].

The CWR process is also used as an intermediate step in forging preforms with less material waste. Rolling can be employed before or after the forging without reheating. The combination of CWR and forging steps can increase the durability of forging tools and even the production of burr-free parts [3].

Figure 1 - Examples of parts produced by cross wedge rolling [4].

CWR tools are mounted on rolling mill rolls or flat plates. The basic geometrical parameters of the process are shown in Figure 2, which presents a process model. These parameters include forming angle, stretching angle, generatrix diameter, final product diameter, and the length of the rolled section [5].

The tools consist of three distinct zones: stamping, drawing, and finishing. In the coining zone, the wedge gradually sinks into the material to a depth of thereby reducing the diameter of the generatrix to . In the forming zone, a spiral reduction occurs along the entire length of the rolled shaft due to the impact of the side walls of the wedge. In the finishing zone, the part undergoes a rotary reduction, during which all the shape irregularities generated in the previous stages of the process are removed [5].

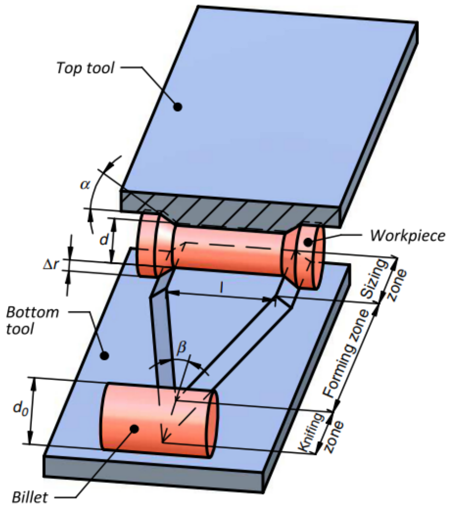

Figure 2 - Schematic of the cross rolling process with flat tools [5].

The basic geometrical parameters of the tools used in the cross wedge rolling process are the forming angle α and the spreading angle β. These angles have a very significant influence on the process, determining the stability of the production, the values of the forces that occur during rolling, and the occurrence of defects in the produced parts. The most common defects are uncontrolled sliding of the formed material between the tools, stricture with the formation of a neck in the part, and internal cracks in the formed product [6]. Figure 3 shows some common defects arising from the cross-wedge rolling process.

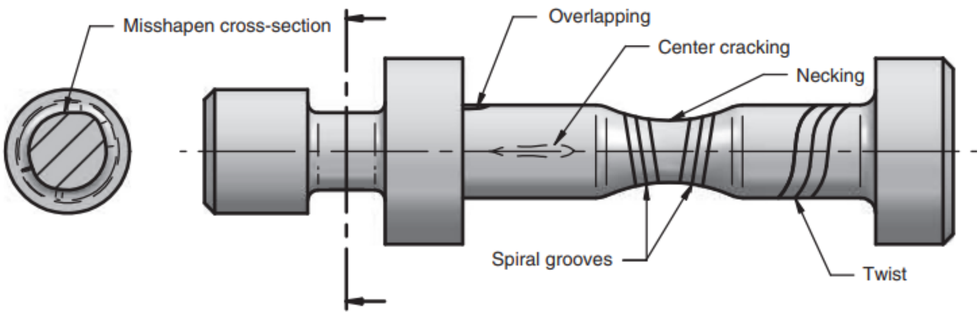

Figure 3 - Defects in parts produced by CWR [5].

These defects usually occur as a result of incorrect selection of tool geometric parameters. The values of the forming angle α must remain between 15° and 40°. Larger values cause a significant increase in axial force and can generate neck formation on the workpiece. In the flare angle β, the range between 3° and 15° is recommended. Increasing the value of the flare angle causes the tools to lengthen while exceeding 15° can cause uncontrolled sliding between the work material and the tools [7]. Overlap on the surface of the formed product can occur when the value of the spreading angle is greater than 35° [8].

The angle β can be defined from Equation 1 [9]:

$$sen\beta = 0{,}009\frac{\mu}{sen\alpha} sen\beta = 0{,}009\frac{\mu}{sen\alpha}$$ (Equation 1)

The dimensioning of the tools must still respect three conditions. The first condition (Equation 2) aims to keep the process stable without slipping. The second condition (Equation 3) determines the limit value to avoid part strangulation. The last condition (Equation 4) inhibits the occurrence of cracks in the axial area of the formed product [1].

$$(0{,}25 + 0{,}0038\alpha)\beta^{0{,}925} \leq 1{,}93(0{,}25 + 0{,}0038\alpha)\beta^{0{,}925} \leq 1{,}93$$ (Equation 2)

$$\frac{\sqrt{2tg\alpha\ .tg\beta}}{\pi}\left(1+\frac{1}{\delta}\right)(\delta - 1) \leq 1{,}93\frac{\sqrt{2tg\alpha\ .tg\beta}}{\pi}\left(1+\frac{1}{\delta}\right)(\delta - 1) \leq 1{,}93$$ (Equation 3)

$$(0{,}115 + 0{,}0038\alpha)\beta^{0{,}325} \leq \frac{0{,}35}{0{,}4}(0{,}115 + 0{,}0038\alpha)\beta^{0{,}325} \leq \frac{0{,}35}{0{,}4}$$ (Equation 4)

Where is the forming angle, is the spreading angle, is the coefficient of friction, and is the strain ratio expressed as a function of the billet diameter and the conformed step diameter [9]:

$$\delta = \frac{d_0}{d}\delta = \frac{d_0}{d}$$ (Equation 5)

Liu et al. (2014) showed that the maximum allowable strain ratio in cross-wedge rolling do not exceed. In turn, Li (2003) presented that applying too small strain ratios can cause cracking in the component. According to Li, the allowable strain ratio is a function of many variables, such as the angle of widening β, the forming angle α, the rolling temperature, and the grade of the metal worked.

3 MATERIALS AND METHODS

In this work, the specificities of cross wedge rolling tool designed were presented using an axisymmetric preform for the forging process as a point of investigation. The geometry, as shown in Figure 4, consists of the preform of a connecting rod. Thus, it presents a concentration of volume at the ends to favor the formation of the rings of the part in the final forging operation.

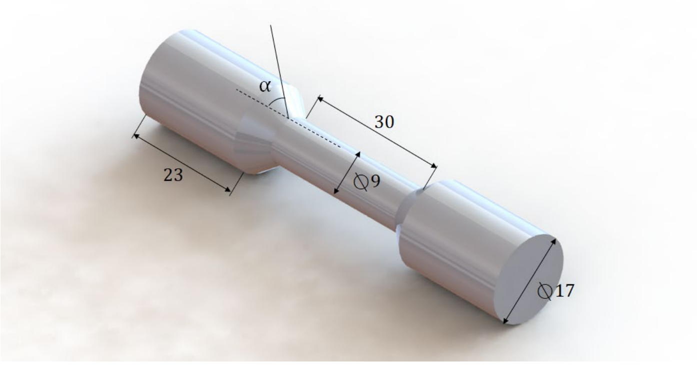

Figure 4 - Detail of the investigated geometry.

The geometry is characterized by a significant diameter reduction with an initial diameter of 17 mm and the final diameter of 9mm. This means that the final step of the part is formed by a strain ratio. This diameter reduction can be achieved by a single wedge forming in only one stage [2, 12]. For this purpose, a cylindrical die with a diameter of 17 mm and a length of 40 mm is used in the rolling process shown schematically in Figure 5.

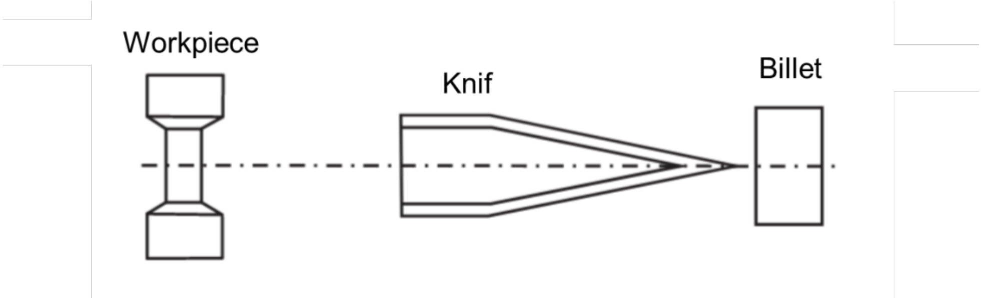

Figure 5 – Schematic drawing of the investigated cross wedge rolling process.

The billet material was SAE 4140 with the process temperature at 1150°C. The analyzed cross-wedge rolling is a pre-forming operation for a subsequent hot forging operation. Thus, it is critical that the temperature after rolling is within the hot working range of the steel. The need for reheating would make the forming sequence unfeasible from a productivity and cost standpoint.

The Forge 3.2 software was used to optimize the tool design by finite element analysis. The numerical model of the process (Figure 6) consisted of two identical flat wedge tools and a cylindrical billet. The only tool that moves during the forming process is the upper wedge at 300 mm/s speed, while the lower wedge was fixed. Therefore, the tools are considered rigid to reduce the computational effort. The generatrix is assigned as an elastoplastic behavior, with the geometry being discretized into triangular elements. The properties of SAE 4140 steel are available in the software's material library. Table 1 presents the input parameters of the numerical model of the cross rolling process. In cross-wedge rolling processes, the friction that occurs is characterized by high values of coefficient of friction ranging from 0.8 to 0.9 [13]. In the numerical models, a value of $\mu = 0{,}8$.

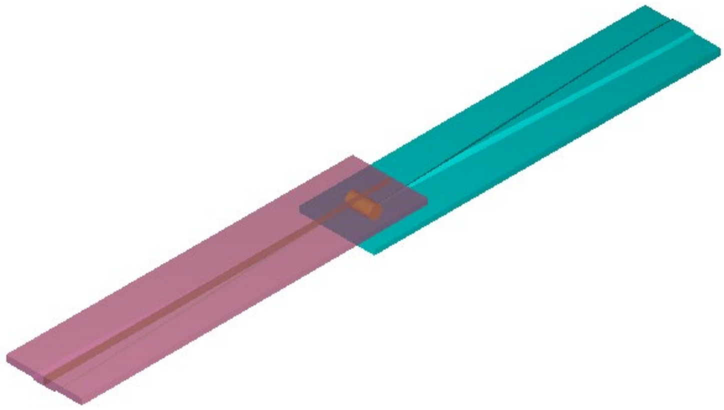

Figure 6 - Numerical model of the cross wedge rolling process.

Table 1 - Input parameters of the numerical model of the cross rolling process.

Mesh Type	Triangular
Mesh Size	1 mm
Billet material	SAE 4140
Die temperature	1150 °C
Tooling temperature	150 °C
Tool material (rigid)	AISI H13
Friction coefficient	0,8
Tool speed	300 mm/s
Heat Transfer Coefficient	10 kW(m².K)

4 RESULTS AND DISCUSSIONS

The cross wedge rolling tool with the geometric parameters defined by numerical simulation is shown in Figure 7. The tool length is 550 mm. This value influences the selection of the forming machine. Tools of high lengths require the use of more robust machines. In this context, the defined length does not represent a limitation. The numerical results show that the axisymmetric preform can be produced by tools with the forming angle (α) set to 30° and the reaming angle (β) to 3°.
Several simulations were necessary with different combinations of α and β to define the geometric parameters of the tool. The use of other tool angle values resulted in defective parts. As an example presented in figure 8, a part produced with defects was due to wrong parameterization. It shows that geometry does not reach the target dimensions due to uncontrolled sliding. In other simulations, parts with neck formation were also observed.

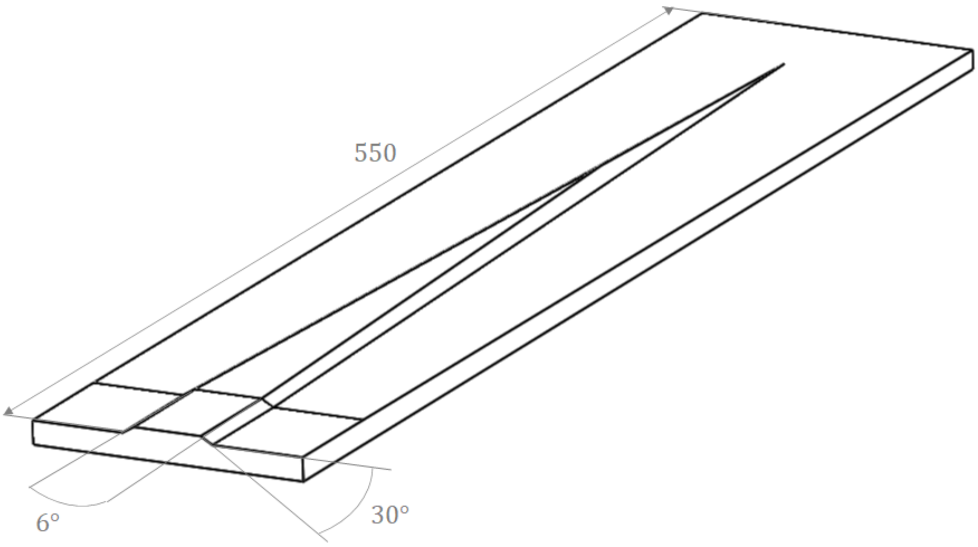

Figure 7 – Cross wedge rolling tool.

The distribution of equivalent strains in the rolled part is shown in Figure 9. At the end of the process the maximum value of $\varphi_{eq} = 8$ is observed at the entrance of the slope connecting the smallest and largest diameter. The distribution is typical of cross wedge rolling processes. The deformations resemble ring-shaped layers, with their highest values located on the outer surfaces. This results from the action of frictional forces that make the material flow in a circumferential direction, causing redundant deformations [14].

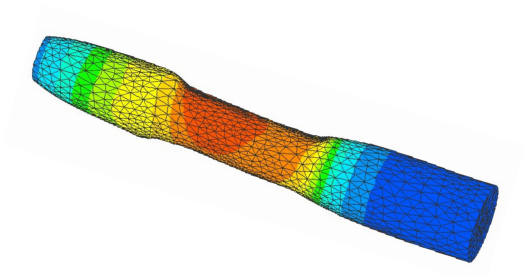

Figure 8 – Example of generated geometry with defects due to wrong parameterization.

Figure 10 shows the temperature distribution on the produced part. The results show that the relatively short forming time of approximately 1.6s limits the thermal exchange and the temperature of the material remains in the hot working range. At the end of the process the part presents temperatures between 1119 and 1219°C. The forming work is responsible for the temperature increase observed in the region where the deformation level was higher. The largest temperature drops can be observed in the regions of the part that were formed first and then only remained in contact with the tools

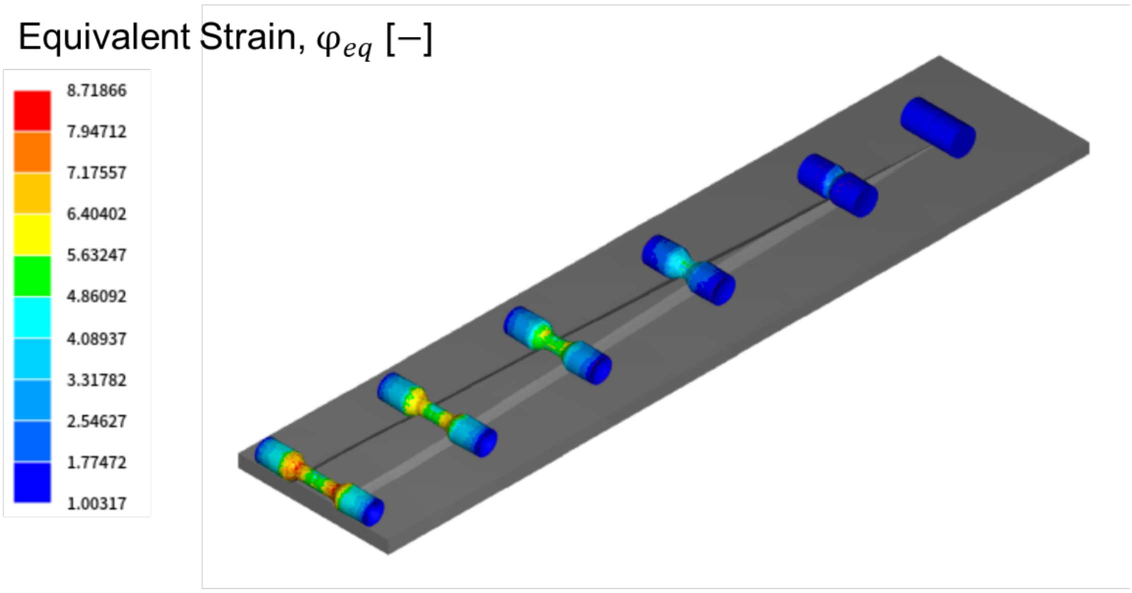

Figura 9 – Numerical result of the equivalent strain distribution in the laminate geometry.

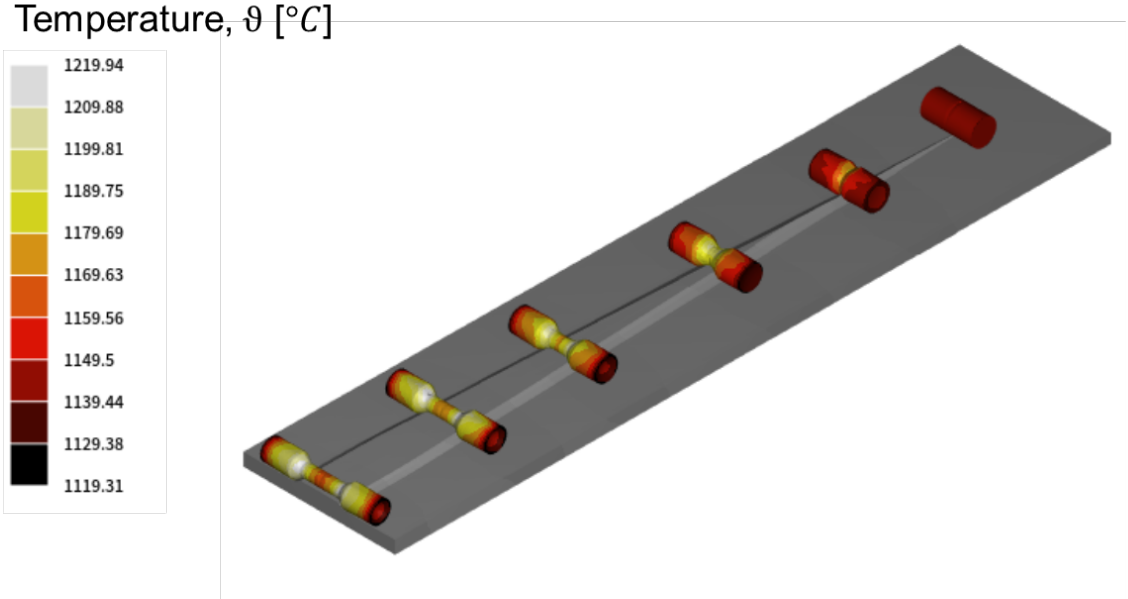

Figure 10 - Numerical result of the equivalent strain distribution in the laminate geometry.

Figure 11 presents the distribution of tangential stresses σ_x acting in the direction in which the tools move, while Figure 12 shows the distribution of radial stresses acting perpendicular to the tool surface. The stress state developed in the cross wedge rolling process is typical of rotary compression in which the initial diameter is cyclically reduced by the forming tools until the desired value is reached [2]. It can be seen that the effect of the wedges in the areas adjacent to the tools, the compressive stresses exert an influence on the material. The lowest stresses occur at the surface. The tensile stresses occur in the zones where there is no contact between the rolled material and the tool.

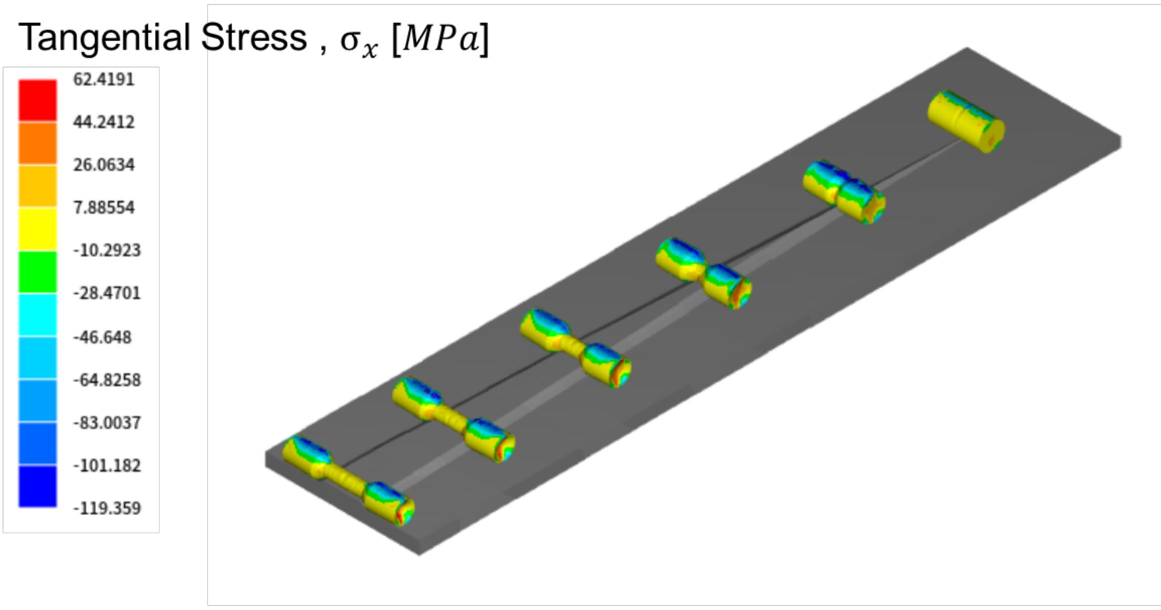

Figure 11 - Numerical result of the tangential stress distribution in the laminate geometry.

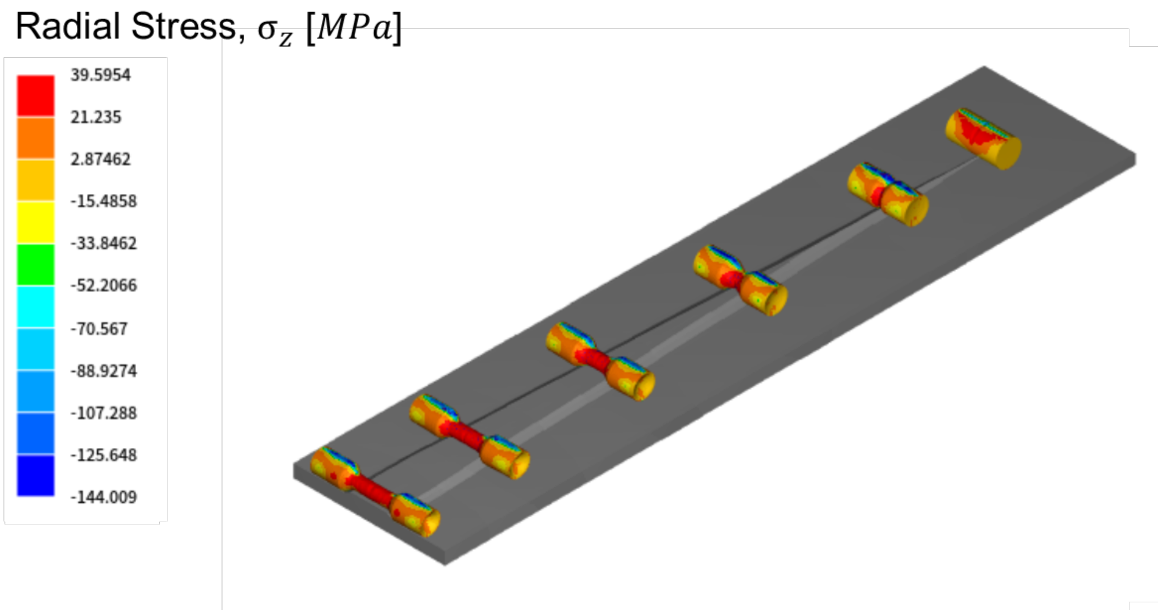

Figure 12 – Numerical result of the radial stress in the laminate geometry.

The prediction of the forming forces is of primary importance with regard to the development of technological mechanical forming processes. Thanks to the determination of the forces, not only can suitable assemblies and safety devices be selected for the rolling process, but also the development of an automatic control system is possible. The force, which affects the wedge in the rolling process can be decomposed into three components: radial (F_z), axial (F_y) and tangential (F_x). The radial component influences the load on the tool and the rolling mill and therefore affects the production accuracy. Knowledge of the tangential force is indispensable for calculating the motor power of the rolling mill. Due to the symmetry of the tool segment, knowledge of the longitudinal (axial) force is not as essential for the selection of a rolling mill [2].

The finite element analysis allowed the determination of the forces developed in the process. Figures 13 and 14 show the evolution of tangential and radial forces, respectively. The variation in force is typical of cross rolling processes [1]. During the coining stage, the forces gradually increase and then decrease during shaft sizing (stretching) [2].

The behavior of the tangential force component depends on the spreading angle. Low values of β cause a significant reduction in the value of the tangential force. As the value of β employed in the tool is close to the lower limit of the range indicated in the literature for a safe process, the force value was low, close to 3.5kN.

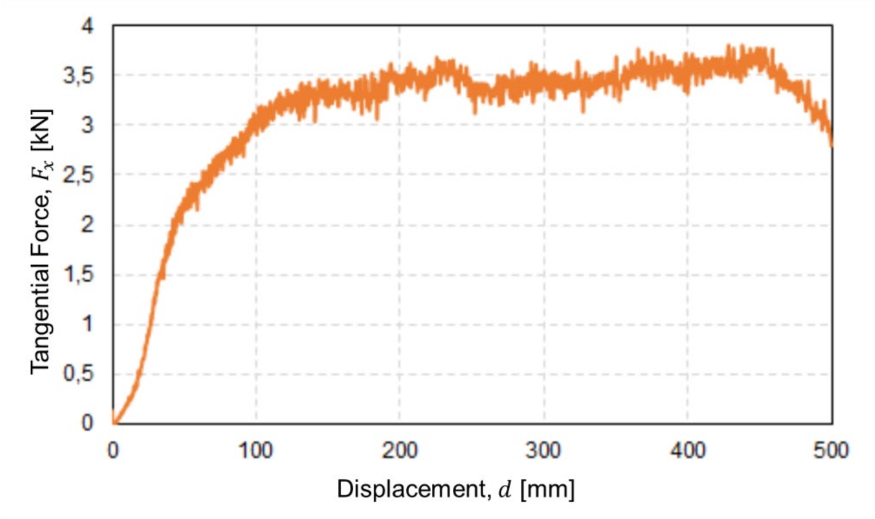

Figure 13 – Evolution of tangential force as a function of displacement of the cross wedge rolling tool.

The radial force distribution depends especially on the forming angle. High values of α result in a decrease in the radial component of the force. Since the proposed tool used a value of α at the upper limit of the range indicated in the literature for a safe process, the force value was moderate, close to 13kN.

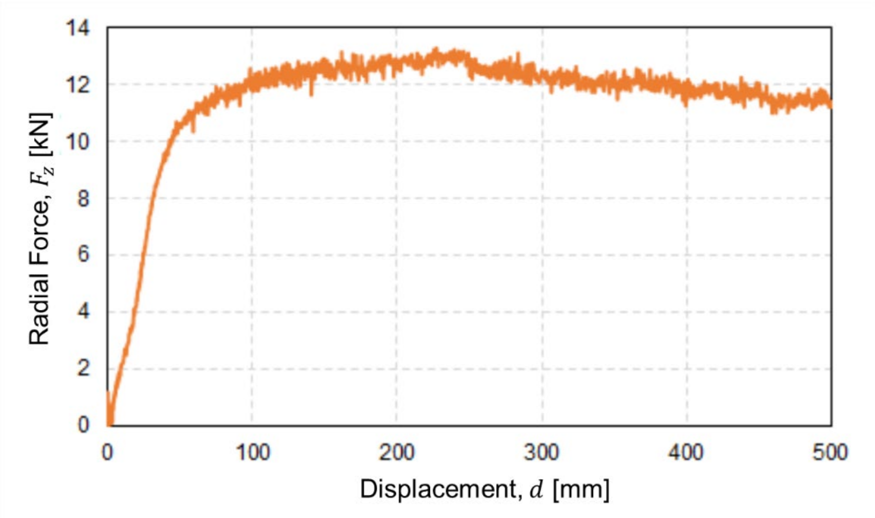

Figura 14 – Evolution of radial force as a function of displacement of the cross wedge rolling tool.

5 CONCLUSION

This paper set out to expose the specifics of cross wedge rolling tool design through numerical analysis of the forming of an axisymmetric forging preform. It was shown that the success of the process depends fundamentally on the correct definition of the geometric parameters of the tools. The angles that form the tool wedge influence not only the ability to obtain a defect-free part, but also the forces developed during forming. In this context, numerical simulation has proven to be an extremely useful tool in defining the optimal parameters for the process, as well as in the selection of the forming equipment.

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