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A Digital Twin-Based Study of Material Behaviour in the Rolling Process

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ABSTRACT

The study proposes the development of a digital twin model for the rolling process. This virtual representation allows for the investigation of how various rolling parameters influence the quality of the final product. By employing finite element analysis (FEA), the model can simulate the rolling process under different conditions.

Specifically, the study focuses only workpiece material which includes aluminum alloy (Al2024) for digital twin scenario. Through simulations, critical parameters like the Z-force exerted on the workpiece can be determined and compared. This enables researchers to evaluate different scenarios and identify optimal rolling conditions without the need for costly physical experiments.

In this way, optimal rolling conditions can be determined without the need for costly physical experiments, and production processes can be improved. It can be said that the digital twin model is an important tool for more efficient and productive production in the rolling industry. In particular, digital twin models supported by FEA offer a groundbreaking approach to production by simulating the complexities of rolling processes in detail. Thus, production processes can be optimized, product quality can be increased, costs can be reduced, and more sustainable production can be achieved. The digital twin is becoming an indispensable tool for more efficient and productive production in the rolling industry.

Keywords: Rolling; Friction coefficient; Roller Diameter; Finite element analysis; Digital twin.

Haddelenme Sürecinde Malzeme Davranışının Dijital İkiz Temelli İncelenmesi

ÖZ

Çalışma, haddeleme süreci için bir dijital ikiz modelinin geliştirilmesini önermektedir. Bu sanal temsil, çeşitli haddeleme parametrelerinin son ürünün kalitesini nasıl etkilediğini incelemeye olanak tanır. Sonlu elemanlar analizi (SEA) kullanılarak model, farklı koşullar altında haddeleme sürecini simüle edebilir.

Özellikle çalışma, dijital ikiz senaryosu için alüminyum alaşımı (Al2024) içeren yalnızca iş parçası malzemesine odaklanmaktadır. Simülasyonlar yoluyla, iş parçasına etki eden Z-kuvveti gibi kritik parametreler belirlenebilir ve karşılaştırılabilir. Bu, araştırmacıların farklı senaryoları değerlendirmelerine ve pahalı fiziksel deneylere gerek kalmadan optimum haddeleme koşullarını belirlemelerine olanak tanır.

Bu sayede, pahalı fiziksel deneylere gerek kalmadan, optimum haddeleme koşulları belirlenebilecek ve üretim süreçleri iyileştirilebilecektir. Dijital ikiz modelinin, haddeleme endüstrisinde daha etkin ve verimli üretim için önemli bir araç olduğu söylenebilir. Özellikle, SEA ile desteklenen dijital ikiz modelleri, haddeleme süreçlerindeki karmaşıklığı detaylandırılmış bir şekilde simüle ederek, üretimde çığır açıcı bir

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yaklaşım sunmaktadır. Böylece, üretim süreçleri optimize edilerek, ürün kalitesi artırılabilir, maliyetler düşürülebilir ve daha sürdürülebilir bir üretim gerçekleştirilebilir. Dijital ikiz, haddeleme endüstrisinde daha etkin ve verimli üretim için vazgeçilmez bir araç haline gelmektedir.

Anahtar Kelimeler: Haddeleme; Sürtünme katsayısı; Hadde çapı; Sonlu elemanlar analizi; Dijital ikiz.

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1. INTRODUCTION

Rolling can be defined as the sizing or forming of the workpiece by the effect of the compression by passing between at least two rollers rotating in opposite directions around their axes. Rolling is one of the most important plastic forming methods. The plastic forming process can be defined as the production without a mass or chemical change of products (Çapan, 2010; Kayalı, 1995). During rolling, the rollers rotate at the same speed and opposite direction to each other. The workpiece is shaped to the desired geometry as it passes through the rollers. The rolling process is classified into two groups as cold and hot rolling. If the rolling process performs above the recrystallization temperature of the workpiece, it is called hot rolling. If the rolling process performs below the recrystallization temperature of the workpiece, it is called cold rolling. In hot rolling, large deformations of the workpiece occur. The main purpose is to form the workpiece. In cold rolling, the purpose is to shape the workpiece as well as to increase strength by the strain hardening of the workpiece during the process and to give the final forming of the product. The surface quality and dimensional tolerance values of the products produced by cold rolling are very high (Groover, 2010). In order to produce the final product of desired quality after the rolling process, rolling parameters should be determined in the best way. These parameters are the friction coefficient, the structure of the workpiece, the diameters of the rollers, the rolling speed, the rolling temperature, and they are among the most important factors determining product quality. All of these parameters are generally designed from prior experience. However, since rolling systems are costly systems, the smallest error in the design of rolling systems leads to serious cost loss. It is very important to know or predict in advance how these parameters affect the rolling system.

Computer aided finite element analyses (FEA) and computational fluid dynamics (CFD) were used to solve mechanical properties of processes, simulations of COVID-19 and other infections and optimal configuration of implant materials (Gök et al., 2014; Gök, 2015; 2021a; 2021b; Gök & Gök, 2024; Gök, Gök & Kişioğlu, 2019; Gök et al. 2019; Gök, Selçuk & Gök, 20121; Pirhan, Gök & Gök, 2020).

This study proposes the development of a digital twin model to simulate the rolling process. By leveraging FEA, the model can accurately predict the behaviour of the work piece under various rolling conditions. Key parameters such as friction coefficient can be systematically varied to assess their impact on the final product quality. Specifically, the study focuses only on commonly (Gök et al., 2014; Gök, 2015; 2021a; 2021b; Gök & Gök, 2024, Gök et al., 2019a; Gök et al., 2019b; Gök et al., 2021; Pirhan et al., 2020) used work piece material which includes aluminium alloy (Al2024), Through simulations, critical parameters like the Z-force exerted on the workpiece can be calculated and compared. This allows for the identification of optimal rolling conditions without the need for costly physical experiments. By employing a digital twin approach, researchers can significantly reduce time and cost associated with traditional experimental methods while gaining valuable insights into the rolling process.

2. ROLLING PROCESS

Rolling, which is one of the mass forming methods, is a process of plastic forming which is defined as resizing or forming the workpiece by passing between two rollers, which rotate in opposite direction to each other and which are called rollers. Figure 1 is a schematic representation of the rolling process.

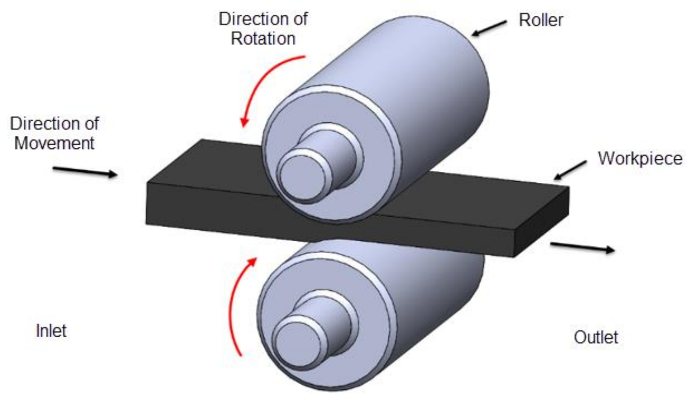


Figure 1: Schematic representation of the rolling process

2.1 Forces in Rolling Process

During the rolling process, two different fundamental forces act on the workpiece. As shown in Figure 2, these forces are the radial force (Pr) and the tangential friction force (Fs). Pr can be defined as rolling force or compression force. Fs is defined as the frictional force that occurs along the arc in which the workpiece and the roller contact. The force Fs is critical for the start of the rolling process. Fs can be calculated by multiplying Pr and friction coefficient (μ) in Eq. 1. When the horizontal components of the forces Pr and Fs shown in Figure 2 are examined, three different situations arise. These situations are explained by equations (2), (3) and (4).

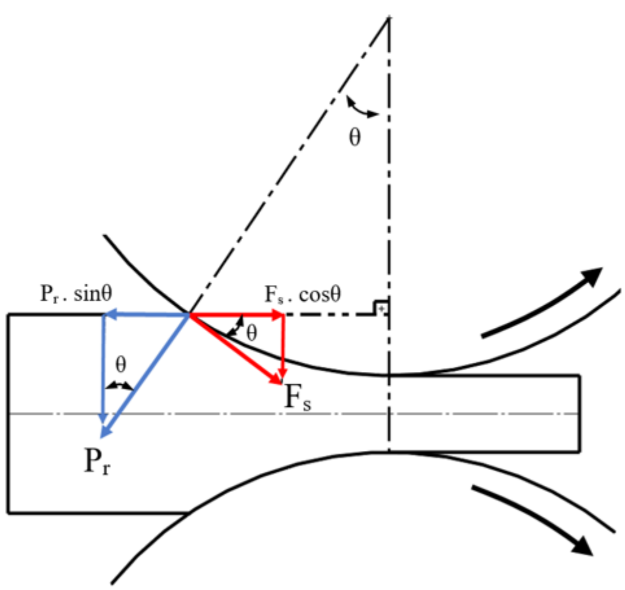


Figure 2: Forces during the rolling process

$$\mathbf{Fs = N.}\ \mu \tag{1}$$

$$\mathbf{Fs.cos\theta > Pr.sin\theta}\ \text{ ise }\ \mu > \tan\theta \tag{2}$$

$$\mathbf{Fs.cos\theta = Pr.sin\theta\ \ ise}\ \ \mu = \tan\theta \tag{3}$$

$$\mathbf{Fs.cos\theta < Pr.sin\theta\ \ ise}\ \ \mu < \tan\theta \tag{4}$$

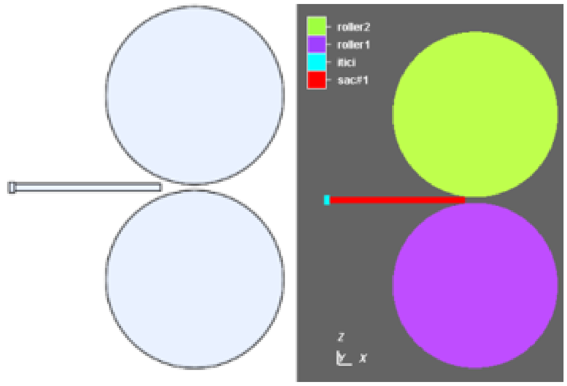
When the equations and Fig. 2 are examined, the condition in Eq. (2) is required to start the rolling process. In other cases, the workpiece cannot be pulled between the rollers. The workpiece is pushed back from the rollers and the rolling process cannot start due to insufficient friction force (Çapan, 2010; Esen, 2019; Groover, 2010; Kayalı, 1995).

3. MATERIALS AND METHODS

In this study, the different rolling parameters were analyzed and it was aimed to find optimum rolling parameters and to investigate how these parameters affect the rolling process by using FEA. The process parameters were given in Table 1. During the analysis, the thickness of the workpiece with dimensions of 500 x 230 was reduced from 25.4mm to 20.3mm by cold rolling method. The rolling system was modeled in Solidworks in three dimensions. As a finite element program, Simufact Forming program, which is powerful especially in the field of plastic forming, was used (Figure 3).

Table 1: Process parameters

Friction coefficient	Material Types	Roller Diameters
0,1	Al2024	610mm
0,2		
0,3		
0,4		
0,5		
0,6		
0,7		
0,8		
0,9		
1		



a) b)

Figure 3: a) 3D modeling of rolling system b) Finite element model

4. NUMERIICAL ANALYSIS

Numerical analyzes were performed using FEA and the results were examined according to friction coefficient, material type and roller diameter. In the Simufact Forming program, the vertical component of the rolling force shown in Figure 4 was compared. The vertical component of the rolling force is called the Z Force.

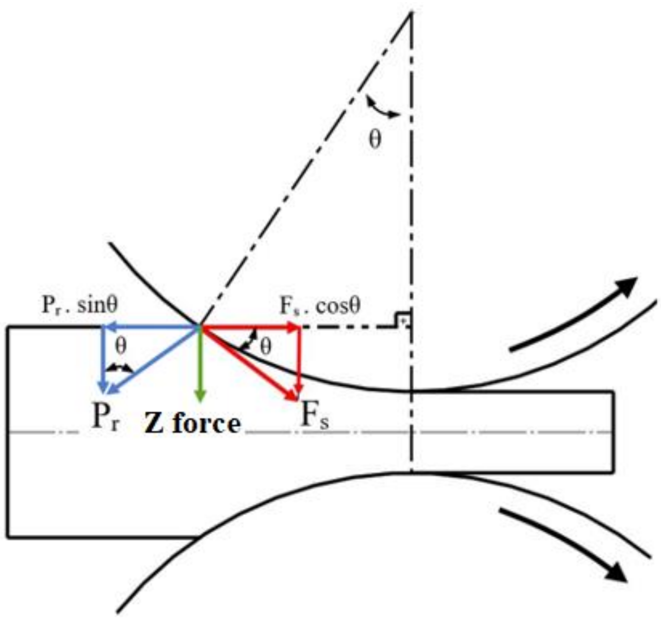


Figure 4: Representation of Z Force

4.1. Effect of Friction, Material, and Roller Diameter on the Rolling Process

A digital twin model was utilized to investigate the influence of the friction coefficient on the rolling process. Simulations were conducted for the Al2024 material with varying friction coefficients (0.1-1.0). Results indicated that increasing the friction coefficient generally leads to higher Z-force. These findings align with previous studies and provide valuable insights for optimizing rolling processes and material selection (Figure5). When the numerical analyzes made for three different materials according to the friction coefficients are examined, it is seen that as the value of the friction coefficient increases, the force Z is increased. Gunasekera et al. (1998) have shown that the results are in this direction. In addition to these results, it was found that μ value does not affect Z Force after a certain value. When the graphs are examined, the optimum value of the friction coefficient can be taken as 0.3.

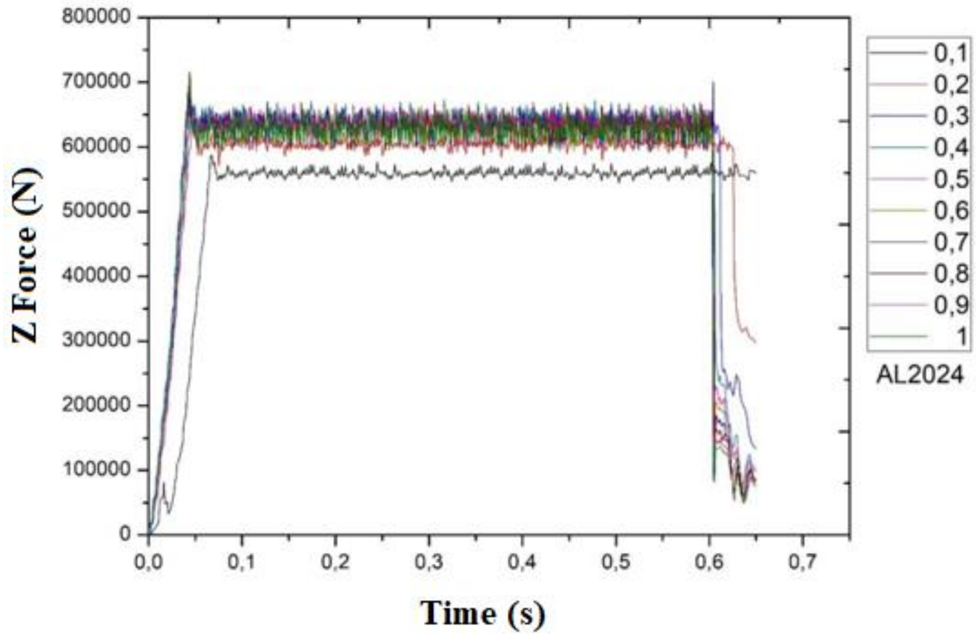


Figure 5: Z Force varition at different friction coefficients for Al2024

4.2. Proposal of a digital twin model for Rolling process

A digital twin is a virtual replica of a real-world entity, such as a product, system, or process. This digital counterpart enables various applications, including simulation, integration, testing, monitoring, and maintenance. Originally conceived as a cornerstone for Product Lifecycle Management, digital twin technology is now poised to revolutionize precision medicine by facilitating personalized diagnoses and treatments (Grieves, 2002; T. Sun, He, & Li, 2023). Figure 6 illustrates a practical application of digital twin technology. On the other study presented a method to improve manufacturing quality by using a digital thread to analyze product data and adjust production steps accordingly (Liu, et al., 2023). Another paper aimed to improve the performance of hot rolling process control systems by using a digital twin to analyze system performance, identify issues, and optimize controller parameters (Sun, et al., 2024). Another paper aimed to reduce vibration in a continuous rolling mill by using a digital twin to optimize process parameters and improve real-time data accuracy (Hu et al., 2024). The paper aimed to improve the quality and efficiency of roll forming processes by developing a digital twin model and a product-oriented feature data management framework to analyze complex data and optimize process parameters (Ren et al., 2024).

Digital twin technology offers significant potential to optimize key parameters in rolling processes, such as friction coefficient, temperature, speed, and pressure, enhancing both efficiency and product quality. By simulating these parameters, the digital twin helps understand complex deformation mechanisms; for instance, increasing the friction coefficient raises the Z-force on the workpiece, but this force eventually saturates. Through virtual testing, digital twins reduce energy consumption, improve surface quality, and minimize material waste. Thus, digital twin technology is crucial for creating more sustainable and high-quality rolling processes.

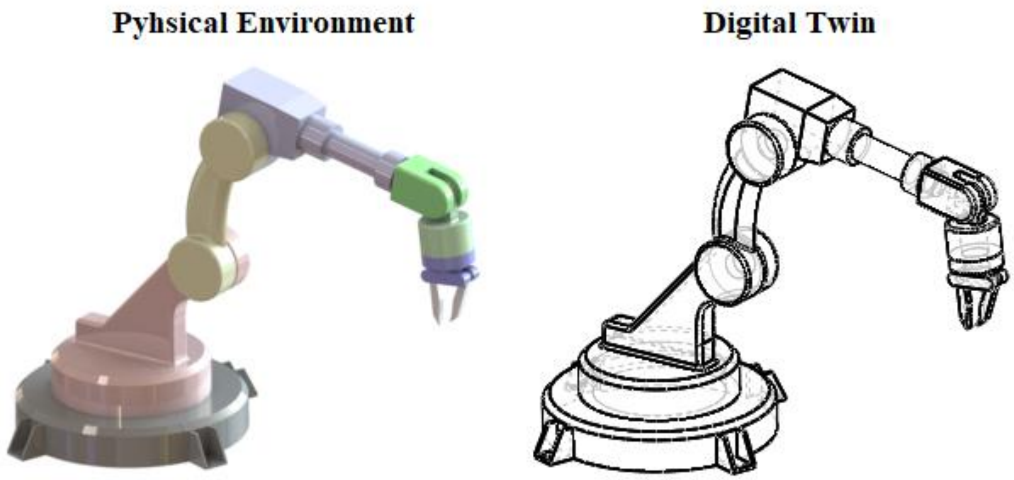


Figure 6: Application of digital twin technology

Results indicated that increasing the friction coefficient generally leads to higher Z-force, aligning with previous studies. However, the model also revealed a saturation point, beyond which further increases in the friction coefficient did not significantly affect the Z-force. Importantly, the digital twin model can be used to predict the induced stresses and strains within the material, allowing for analysis of potential fatigue and wear. By optimizing the friction coefficient, it is possible to minimize these effects and extend the lifespan of the rolling mill components. The model's ability to simulate real-world conditions and predict the impact of process parameters makes it a valuable tool for improving the efficiency and durability of rolling processes.

5. CONCLUSION

This study investigates the influence of key rolling parameters, such as the friction coefficient on the deformation behavior of the workpiece during the rolling process. A digital twin model, supported by FEA, was employed to simulate the complex deformation mechanisms and predict the resulting stress and strain distributions within the workpiece. The study found that as the friction coefficient increases, the Z-force exerted on the workpiece also increases, but beyond a certain critical friction coefficient value, the Z-force tends to saturate. The optimal friction coefficient range was determined to be between 0.2 and 0.4 for all materials considered. The digital twin model proved valuable in optimizing the rolling process, reducing energy consumption, and improving product quality by simulating various scenarios. This study provides valuable insights for developing more efficient and sustainable rolling processes for a wide range of materials.

Digital twin technology shows great promise for future manufacturing by enabling detailed simulations that optimize production parameters. This study demonstrates how digital twins can reduce energy consumption, improve material efficiency, and enhance product quality by analyzing the effects of friction on deformation in the rolling process. With capabilities to simulate and validate complex mechanisms, digital twins are set to become essential tools, supporting more efficient, sustainable, and innovative manufacturing methods.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to this work.

CONTRIBUTIONS OF AUTHORS

K.G.: Methodology, investigation, writing—review and editing.

C. E.: Finite element analysis, original draft preparation, resources.

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