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The effect of rolling direction and strain rates on the tensile properties of AA2024-T3 aluminum alloy

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Abstract: The AA2024-T3 alloy is a lightweight and durable material commonly used in the aerospace industry. This study investigates the impact of the rolling direction (RD) and strain rates on the alloy's tensile properties. Tensile tests have been performed on samples oriented parallel and transverse to the rolling direction at varying strain rates (5, 25, and 125 mm/min). Samples parallel to the rolling direction have exhibited higher strength compared to those in the transverse direction (TD). At a strain rate of 5 mm/min, the maximum tensile strength in RD samples has been 530.72 MPa, while in TD samples, it has been 505.76 MPa. At 25 mm/min, the tensile strength has been 498.31 MPa in RD and 482.91 MPa in TD. At 125 mm/min, the tensile strength has been 508.52 MPa in RD and 480.36 MPa in TD. The increase in strain rate has had a complex effect on the mechanical properties. The total elongation values have also varied with strain rate, with the highest total elongation observed at 5 mm/min (0.168) in both RD and TD directions. These findings have highlighted the significant impact of the rolling direction and strain rate on the mechanical properties of the AA2024-T3 alloy, which should be considered in design and manufacturing processes.

Keywords: AA2024, rolling direction, strain rate, formability.

1. Introduction

In many industrial sectors, including energy, machinery, transportation, and aerospace, shaped semi-finished products are commonly used. Material selection for these products is based on the required mechanical properties, and the production method is also a crucial factor. Rolling is a significant plastic shaping method that alters the crystal structure of the material, resulting in anisotropic properties. Anisotropic behavior refers to the phenomenon where materials exhibit different mechanical properties in different directions. This behavior affects the mechanical properties of the material [1-5]. The strain rate used in production processes is another parameter that significantly affects the mechanical properties [6-10]. Strain rate also causes changes in dislocation movements, leading to variations in strength levels. The heat generated during deformation also affects dislocation movements.

The rolling process is known to have a variable effect on the mechanical behaviors of materials [11-15]. In particular, this impact on tensile properties is a critical factor in the development of materials' anisotropic characteristics. In this regard, research has shown that the direction of rolling alters the material's fundamental mechanical properties, such as microstructure, strength, modulus of elasticity, and fracture toughness. Goli and Jamaati [16] investigated the effect of the deformation path applied during the cold rolling process on the microstructure and mechanical properties of the AA2024 aluminum alloy. They emphasized that the average grain size decreased due to dynamic recrystallization in samples that underwent cross rolling. Pang et al. [17] examined the anisotropy

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of the cold-rolled AA2024-T3 aluminum alloy using a laser imaging sensor. Furthermore, they demonstrated that the Yld2004-18p model accurately represents the anisotropic behavior of AA2024-T3 in finite element analyses. Aghabalaeivahid and Shalvandi [18] developed a microstructure-based crystal plasticity model to model the anisotropic plasticity and yield behavior of the AA2024-T3 aluminum alloy. In their work, they mentioned that crystal plasticity modeling based on the actual microstructure could be a useful tool in understanding and predicting the anisotropic behavior of the AA2024-T3 aluminum alloy. Anijdan et al. [19] demonstrated that the combination of cold rolling and suitable aging heat treatment alters the mechanical properties and microstructure of the AA2024 aluminum alloy. It has been stated that cold rolling, double-stage aging, and over-aging treatments have significant effects on the strength of the AA2024 aluminum alloy [20]. These processes lead to changes in the alloy's mechanical properties and microstructure. It has been observed that the mechanical properties of aged samples significantly improve with the correct application of cold deformation. In a study on the microstructure of the AA2024 aluminum alloy in a semi-solid state [21], the impact of rolling and extrusion processes on microstructural conditioning and change has been examined. The results of the study provide important insights into the formability of the alloy in its semi-solid state. It is said that the higher the deformation rate, the smaller the initial particle size, and a 30% thickness reduction is sufficient to achieve a fine distribution of Al-α particles. In tensile tests conducted in three different rolling directions on the AA2024-T351 aluminum alloy, it has been indicated that samples rolled perpendicular to the rolling direction exhibit higher yield strength and ductility characteristics. These characteristics are significantly better compared to those rolled in the thickness direction [22]. The importance of anisotropy in accurately predicting the deformation behavior of materials has been emphasized. In a study that examined the effect of rolling direction on the AA5083 aluminum alloy [23], it has been shown that the process has a significant effect on the tensile properties of the samples. Furthermore, it has been highlighted that when the directional angle increases, tensile strength increases and modulus of elasticity decreases. In a study investigating the effect of cold rolling and subsequent heat treatments on the microstructure and mechanical properties of the AA5052 aluminum alloy [24], it has been shown that an increasing rolling rate elongates the grains of the alloy, and it enhances its strength but reduces its ductility. It has been shown that the AA7050-T7451 alloy exhibits specific internal structural features after rolling, which affects the material's strength properties [25]. The sample to be perpendicular to the rolling direction has achieved the highest tensile strength, whereas the lowest has been obtained in the thickness direction. Rout [11] investigated the effect of different rolling directions on the microstructure and tensile properties of 304 austenitic stainless steel. It has been shown that cross rolling (CR) and reverse rolling (RR) processes have significant impacts on tensile properties. Medjahed et al. [13] studied the effects of different rolling directions (0°, 45°, and 90°) on the microstructure, strength, and anisotropy properties of the Al-Cu-Li-Mg-X alloy. Different rolling directions have been shown to lead to distinctive microstructures that affect the properties.

Another parameter that affects mechanical properties is the strain rate. It is known that the strain rate affects the tensile and fracture strength of the alloy [26, 27]. Understanding these effects is important in determining the production method. Wen et al. [28] have investigated the effects of deformation parameters (strain rate and temperature) on the hot tensile deformation and fracture behaviors of a high-strength steel. Their work has shown that the hot tensile behavior of the material is largely influenced by the relationship between damage formation, hardening, and dynamic softening. As the deformation rate has increased from 0.01 to 10 s-1, uniform fracture morphologies have gradually transitioned to serrated fracturing. That is, the strain rate affects the fracture mechanism, and thus, the mechanical properties are affected. It has been emphasized that changes in the number of voids or cracks in the microstructure increase with a rising strain rate or decreasing tensile temperature. It has been stated that intergranular fracture occurs at high tensile temperatures and low deformation rates, while intragranular fracture occurs at low tensile temperatures and high deformation rates. Kami et al. [29] examined the effects of strain rate on the mechanical properties of AA5021 and commercially pure aluminum (A1070). It has been shown that the AA5021 alloy exhibits negative strain rate sensitivity within a certain strain rate range but displays positive strain rate sensitivity at high strain rates. It has been stated that the primary factor is due to the effect of Mg atoms locking the dislocations. Ma et al. [30] investigated the variation of mechanical properties at various strain rates in the 5A02-O aluminum alloy. They have shown that significant increases in yield and tensile strength occur at high strain rates. It has been stated that a higher strain rate leads to a higher dislocation density. Bobbili et al. [31] conducted tensile tests on the AA7017 alloy at various strain rates and temperatures. It has been observed that strength increases with increasing strain rate. Chen et al. [32] studied the mechanical behavior of AA6xxx and AA7xxx aluminum alloys across a wide range of strain rates. They have conducted standard tensile tests at low and medium strain rates and split-Hopkinson tests at high strain rates. It has been found that AA6xxx series alloys do not show a significant change in strain rate, but AA7xxx series alloys exhibit a moderate level of rate sensitivity. They have also shown that there is no significant difference in rate sensitivity among different rolling directions in their studies. Wang et al. [33] investigated the effects of strain rate on the mechanical properties and microstructure of the Al-Mg-Si-Cu alloy. It has been stated that increasing the strain rate enhances the alloy's strength but has a limited effect on the microstructure. Aydın et al. [34] studied the impact of strain rate and rolling direction on the tensile properties of dual-phase steels used in the automotive industry. They have shown that both strain rate and rolling direction has a significant impact on the material's tensile properties. Additionally, they have emphasized that the strain rate has a more significant effect on the tensile properties than the rolling direction in both steels. In another study by Aydın et al. [35], has been shown that the effect of strain rate on strength is more pronounced in the AA6082-T6 alloy than in the AA1035-H14 alloy. They have highlighted the significant effects of rolling direction and strain rate on the tensile properties of aluminum alloys.

This investigation focuses on the AA2024-T3 alloy, which is known for its durability and corrosion resistance, making it ideal for high-demand applications [36, 37]. The aim of this research is to investigate the impact of rolling directions and varying strain rates on the tensile properties of the AA2024-T3 alloy. While it is well-established that mechanical properties are direction-dependent due to rolling, this study provides a novel analysis of the combined effects of rolling direction and varying strain rates on the tensile properties of the AA2024-T3 alloy. Unlike previous studies that typically focus on either rolling direction or strain rate independently, our research integrates both factors to provide a comprehensive understanding of their interaction and its impact on the material's performance. The results indicate that both the direction of rolling and the applied strain rates significantly affect the mechanical behavior of the alloy.

2. Material and Method

The AA2024 aluminum alloy has a chemical composition characterized by aluminum itself along with copper, manganese, magnesium, and other elements (Table 1). This composition equips AA2024 with properties such as high strength and good corrosion resistance, making it a preferred material in the aerospace sector. In our study, material manufactured in the form of sheet metal and subjected to T3 tempering has been used. The T3 designation represents the mechanical properties obtained after solution heat treatment followed by cooling and natural aging (aging at room temperature). This heat treatment provides the alloy with strength, corrosion, fatigue, and crack resistance.

Test specimens have been cut in air atmosphere using a laser cutting machine according to the ASTM-E8 standard [38]. Specimens with the dimensions specified in **▶Figure 1** have been prepared in two different orientations relative to the rolling process direction (RD and TD to the rolling direction, **▶Figure 2**). With this method, the effect of the rolling direction on the material has been examined in detail. The prepared samples have been subjected to tensile tests at room temperature using a Shimadzu Autograph 100kN brand tensile test machine. The experiments have been repeated three times to ensure the reliability of the results.

In the tensile testing machine, the lower jaw of the device is fixed, while the upper jaw is movable. As shown in **▶Figure 3**, for each tensile specimen, a total measurement area of 50 mm has been marked, comprising 25 mm above and below the center of the specimen's vertical axis. This marked area has been set as the focus point to be clearly visible by the video camera. The

Table 1. Chemical composition of the alloy.

Material	Fe	Si	Cu	Cr	Mn	Mg	Zn	Zr+Ti
AA2024	0.5	0.5	3.8-4.9	0.1	0.3-0.9	1.2-1.8	0.25	0.15

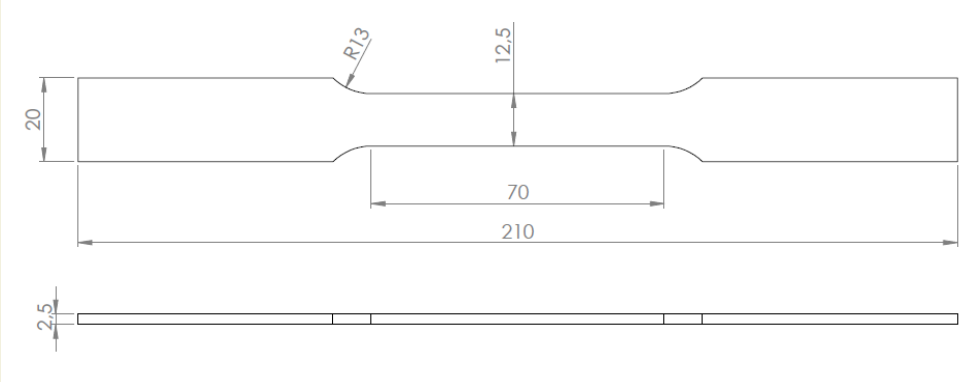

Figure 1. Dimensions of the tensile test specimen (mm).

determination of elongation has been conducted using a video-type extensometer. This method allows for the precise recording of deformations experienced by the samples during tension.

3. Results and Discussion

According to the experimental tests performed, these two factors have affected the mechanical behaviors of the alloy. ▶**Figure 4** shows the effect of the rolling direction at a strain rate of 5 mm/min. Specimens parallel to the rolling direction have exhibited higher strength compared to those TD to the rolling direction. This situation is attributed to the material's internal structural characteristics and the orientation of the crystal structure during the rolling process. It is thought that samples parallel to the rolling direction show higher strength due to the alignment of the crystal structure and dislocations. Situations where dislocation movements occur more easily affect the mechanical properties of the material.

Tensile tests conducted at different strain rates (5, 25, and 125 mm/min) are presented in ▶**Figure 5**. Specimens prepared in the rolling direction have different strength values compared to those prepared in the transverse direction (TD). This difference in strength values shows that the material has anisotropic properties, meaning its properties vary depending on the direction. This situation demonstrates that the internal structure and crystal orientation of aluminum alloys affect their mechanical properties. During the rolling process, the orientation of crystal structures within the material aligns with the direction of the applied force.

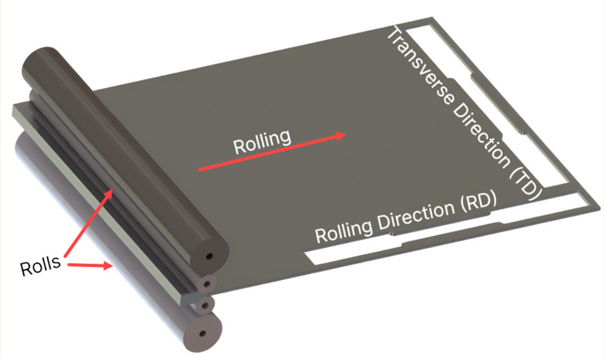

Figure 2. Preparation of samples in different directions on a laser cutting machine.

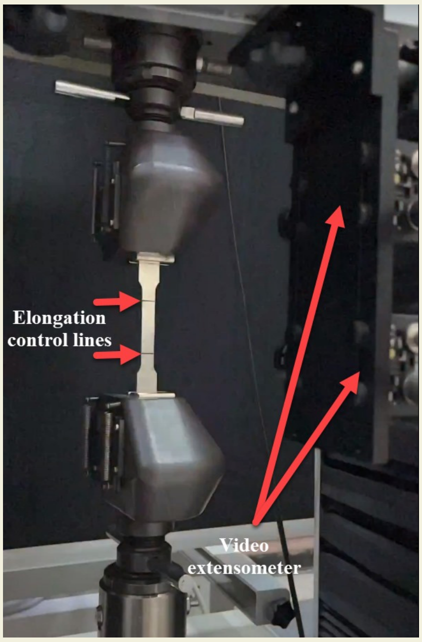

Figure 3. Tensile test setup.

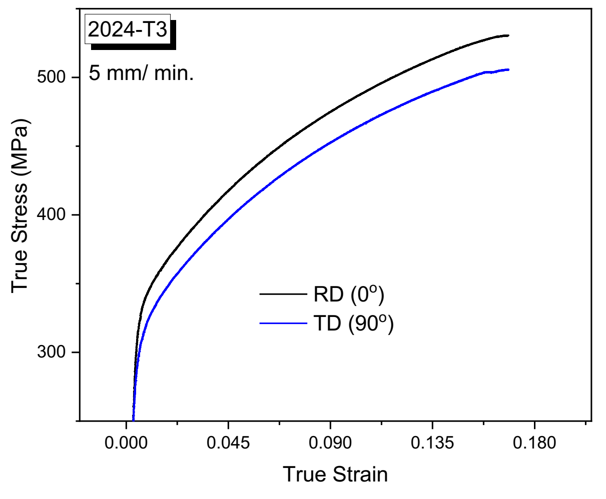

Figure 4. The effect of rolling direction.

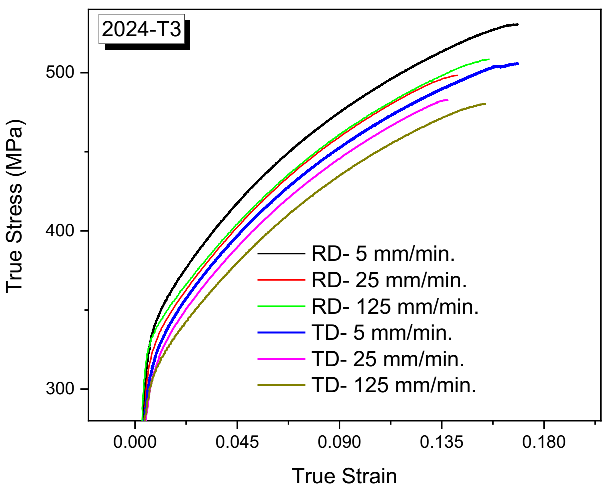

Figure 5. The effect of rolling direction and different strain rates.

This illustrates the significant role of the rolling process on the mechanical properties of the material.

The change in strength as a result of rolling is related to grain orientation. Rolling alters the crystal structure of the material, leading to an alignment of grains in the rolling direction. This alignment affects the movement of dislocations, which are known to move more easily along certain crystallographic planes and directions. According to Goli and Jamaati [16], during the rolling process, the grains become elongated and aligned along the rolling direction, which facilitates dislocation movement in that direction. Similarly, Aghabalaeivahid and Shalvandi [18] noted that the anisotropic behavior of the AA2024-T3 alloy can be attributed to the orientation of grains and dislocations resulting from rolling. This grain orientation reduces the barriers for dislocation movement along the rolling direction, thereby increasing the material's strength in that direction. These mechanisms are well-documented in the literature and support the findings of our study.

►**Figure 6** shows the stress-strain curve of specimens at different strain rates (5, 25, and 125 mm/min). It is observed that the alloy exhibits a non-linear behavior with respect to strain rate. The highest strength has been obtained at a strain rate of 5 mm/min. On the other hand, the lowest strength has been obtained at a strain rate of 25 mm/min. This phenomenon can be explained by the effect of strain rate on the material's microstructural arrangement and dislocation movements. Low strain rates provide sufficient time for dislocations to move and rearrange within the material's internal structure, leading to higher strength values. However, the material may struggle to adapt to these microstructural arrangements at certain speed ranges. This situation results in a decrease in the strength. Although an increase in strain rate is generally known to increase strength, these results demonstrate that this relationship is not always linear. These observations emphasize that strain rate has a significant effect on the mechanical properties of the material and that the relationship between strength and strain rate is complex.

►**Figure 7** presents the stress-strain curves of specimens prepared in the TD at different strain rates (5, 25, and 125 mm/min). According to the data obtained, there is a negative linear relationship between strain rate and stress. The highest strength has been achieved at a strain rate of 5 mm/min, while the lowest strength has been observed at 125 mm/min. This negative linear relationship observed in specimens prepared in the TD can be due to the material having a more homogeneous microstructure in this orientation. As a result, the material exhibits more predictable behavior against increasing strain rates.

The results obtained experimentally are in agreement with findings reported in the literature. Due to the anisotropic properties of the AA2024 alloy, it has been observed that the yield/tensile strengths differ [39]. It has been determined that the highest yield and tensile strength in the AA2024-T4 alloy are exhibited in the rolling direction [40]. Our study has shown through tensile tests conducted in the rolling direction and at different strain rates that there is a non-linear relationship between strain rate and stress. Moreover, in experiments where the material has been stretched in the rolling direction, elongation and stress have been found to be higher compared to specimens prepared in the TD.

It is known that the effect of strain rate causes different types of fracture (intergranular or transgranular fracture) to occur in the material, which in turn affects the strength [28]. Furthermore, it is understood that an increase in strain rate, by locking dislocations in the internal structure of the atoms, provides an increase in

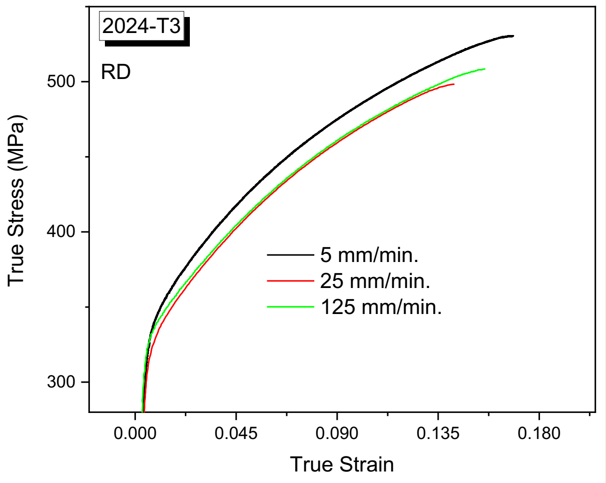

Figure 6. Stress-strain curves for specimens prepared in the rolling direction at different strain rates.

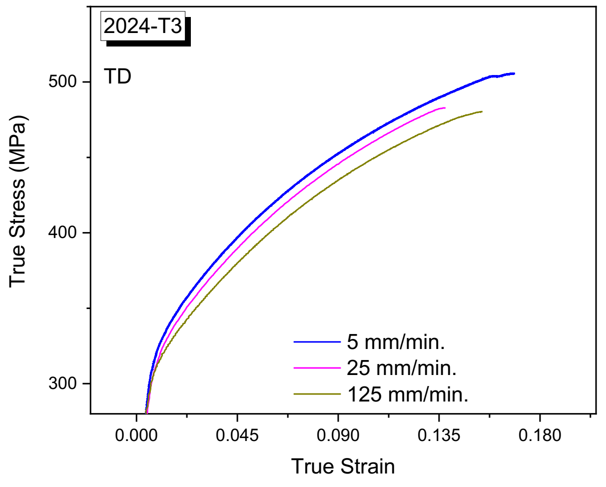

Figure 7. Stress-strain curves for specimens prepared in the TD at different strain rates.

strength. High strain rates have the effect of increasing dislocation density, resulting in increased strength [29, 30]. In experiments conducted at 400 °C on the AA2024 alloy, an increase in strain rate has been observed to increase yield/tensile strength [41]. In the AA2014-T6 alloy, experiments conducted at room temperature have shown that an increase in strain rate also have increased yield and tensile strength [42]. Similarly, the same results have been obtained at different temperatures.

4. Conclusion

In this study, the variations in the mechanical properties of the AA2024-T3 aluminum alloy have been examined in relation to the variations in rolling direction and strain rate parameters. The tensile tests conducted at various strain rates (5, 25, and 125 mm/min) and rolling directions (parallel and perpendicular to the rolling direction) have revealed several key findings:

- *Effect of Rolling Direction*: The tensile strength and elongation of the AA2024-T3 alloy are significantly influenced by the rolling direction. Samples tested as parallel to the rolling direction (RD) have exhibited higher tensile strength and elongation compared to those tested perpendicular to the rolling direction (TD). For instance, at a strain rate of 5 mm/min, the tensile strength in RD samples is 530.72 MPa with an elongation of 0.168, while in TD samples, it is 505.76 MPa with the same elongation of 0.168.
- *Effect of Strain Rate:* The strain rate also has a complex effect on the tensile properties of the alloy. The highest tensile strength has been observed at the lowest strain rate of 5 mm/min, with RD samples showing 530.72 MPa and TD samples showing 505.76 MPa. At a strain rate of 25 mm/min, the tensile strength in RD samples is 498.31 MPa and in TD samples is 482.91 MPa. At 125 mm/min, the tensile strength is 508.52 MPa in RD and 480.36 MPa in TD.
- *Interaction of Factors*: The combined effects of rolling direction and strain rate on the mechanical properties highlight the importance of considering both parameters in the design and manufacturing processes of AA2024-T3 alloy components. The study provides a comprehensive understanding of how these factors interact and influence the material's performance, which can lead to improved application-specific properties.

Overall, the findings of this research highlight the need to optimize rolling direction and strain rate during the manufacturing of AA2024-T3 alloy to achieve the desired mechanical properties. These insights contribute to a better understanding of the anisotropic behavior of the alloy and its implications for industrial applications, particularly in the aerospace sector.

Research Ethics

Ethical approval is not required.

Author Contributions

The author(s) accept full responsibility for the content of this article and have approved its submission.

Competing Interests

The author(s) declare that there are no competing interests.

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Not reported.

Data Availability

Not applicable.

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