Dicle University
Journal of Engineering
https://dergipark.org.tr/tr/pub/dumf
duje.dicle.edu.tr

Research Article

Experimental Investigation of Roughness Transfer Behavior of AA2024-T3 Aluminum Alloys in Cold Rolling

Batuhan ÖZAKIN[1*], Kürşat GÜLTEKİN[2]

[1] Samsun University, Mechanical Engineering Department, batuhan.ozakin@samsun.edu.tr, Orcid No: 0000-0003-1754-949X
[2] Ondokuz Mayıs University, Mechanical Engineering Department, kursat.gultekin@omu.edu.tr, Orcid No: 0000-0002-6790-6822

ARTICLE INFO

Article history:

Received 12 August 2024
Received in revised form 3 February 2025
Accepted 6 February 2025
Available online 26 March 2025

Keywords:

Skin-pass (temper) rolling, Texture transfer, Rough surfaces, Sheet rolling, Surface topography

Doi: 10.24012/dumf.1532363

* Corresponding author

ABSTRACT

Sheet materials are manufactured with roughness in order to be ideally painted and shaped. This process is carried out in the final stage of cold rolling using roughened rolls. The sheet material passing between the rough rolls is finally roughened and put into use. Aluminum alloys are used in many industries due to their superior properties such as light weight, high corrosion resistance and high mechanical properties. This study was carried out to determine the surface roughness behavior of aluminum sheet materials in cold rolling roughening. In this context, AA2024-T3 aluminum alloys were subjected to cold rolling process using roughened rolls at different reduction ratios (1%, 5%, 10%, 20%). During the tests, the rolling forces were read from the test equipment and the roughness parameters R_a, R_v and R_p and roughness profiles of the surfaces roughened by rolling at different reduction ratios were obtained. It was determined that the rolling force and roughness transfer ratio increased as the reduction ratio increased. When the roughness parameters, roughness distribution and surface images were evaluated together in the roughness transfer with cold rolling at 1% reduction ratio, it was concluded that there was a homogeneous roughness distribution on the sheet material surfaces, while the homogeneous roughness distribution gradually deteriorated at 5% and increasing reduction ratios.

Introduction

In the last step of cold rolling, sheet materials with both the desired surface roughness and the desired mechanical properties are manufactured with specially roughened rolls [1]. The last step of cold rolling is known as skin-pass (temper) rolling. One of the most important purposes of this process is to give the surface a roughness texture in order to provide painting and shaping [2, 3]. There are many parameters that affect the roughness transfer to sheet materials in the rolling process. The studies encountered in the literature on these parameters are given below. Mekicha et al. concluded that the most important parameter affecting the topography of the surface in roughness transfer in rolling is the reduction ratio and the rolling speed affects the surface topography to a very small degree [4]. Rodriguez-Vidal et al. stated that the roughness transfer process by rolling strongly depends on the mechanical properties of the materials [5]. Özakın and Kurgan stated in their study that the use of lubricant in the rolling process decreases the rolling force, and a more homogeneous roughness profile is obtained [6]. In a study by Özakın et al., they were stated that in the rolling process applied to materials with different thicknesses at the same reduction ratios, materials with higher thicknesses had more homogeneous roughness distribution [7]. Wu et al. demonstrated the effects of roll diameter, material thickness and roll roughness on roughness transfer to the surfaces of sheet materials by rolling. They showed that larger roll diameter reduces roughness transfer, with more roughness transferred to the thinner strip [8]. Patel et al. showed the effects of roll diameter, reduction ratio and sheet width on roughness transfer using finite element methods. They evaluated the deviation transfer values with their unique methods [9]. Zhang et al. investigated the effects of grinding, polishing and sandblasting processes applied to roll surfaces on surface topography, mechanical properties, and microstructure in the rolling process. They showed that when sheet materials were rolled with rolls produced by sandblasting at the same reduction ratio, they had the highest peak density, the smallest grain size, and the highest tensile strength [10].

It is determined that roughness transfer in the rolling process is intensively applied to sheet steel materials within the literature information. In this direction, aluminum alloys are widely used in high-tech applications due to their many advantageous properties such as light weight, high mechanical properties, good corrosion resistance and cost effectiveness [11-13]. The surface appearance of aluminum sheet materials is one of the important factors that reveal their commercial value, as with all sheet materials. The surface appearance of sheet materials is affected by the rolling parameters of the manufacturing line. Surface quality characteristics of aluminum sheets are expressed as tribological elements between surfaces such as rolling force, forward slip, rolling speed, lubrication conditions, reduction ratio, surface properties of the work roll. It is actually the surface topography of the work roll that determines the surface quality of aluminum sheet materials [14]. The studies encountered in the literature on roughness transfer to aluminum-based sheet materials by rolling are given respectively. Lenard cold rolled AA6061-T6 aluminum alloys with different reduction ratios using mineral lubricant. They investigated the effects of roll roughness on roll force, roll torque and forward slip. They found that the increase in roll roughness did not adequately lubricate the interfaces and caused an increase in roll force [15]. Frolish et al. reported that roll roughness is one of the main factors affecting the surface properties of aluminum sheet materials in rolling [16]. Sun et al. investigated the experimental conditions under which the surface roughness of aluminum materials in the rolling process is optimum. They stated that the reduction ratio and the viscosity of the lubricant play a dominant role in achieving the optimum roughness [17]. Jeng et al. investigated the effects of roll speed, reduction ratio and lubricant viscosity on the surface quality of aluminum sheets from cold rolling parameters. From the theoretical results they obtained, they stated that increasing the reduction ratio, decreasing the roll speed and viscosity will cause an increase in the contact area and an increase in the roll pressure [18]. Hussein et al. investigated the effects of reduction ratio, forming temperature, lubricant properties on surface hardness, surface residual stresses and surface roughness in the rolling process of aluminum alloys. They reported that lubricant properties had a strong effect on surface roughness, while reduction ratio had a strong effect on surface hardness and surface residual stresses [19]. Ma et al. investigated the effects of different lubrication conditions on surface quality after rolling. They showed that water-based nanolubricant exhibited the best properties in terms of surface quality [20]. Warneke et al. produced rough rollers by high-speed laser ablation, characterized the rolls and investigated the transfer of roughness texture to aluminum sheet materials. They stated that the rolls produced by laser ablation technique exhibited more homogeneous roughness distribution compared to those produced by electrolyte etching [21].

When the literature studies are examined, roughness transfer to sheet materials by rolling is generally subject to steel materials and the effects of many parameters in which steel materials are used have been tried to be examined. It has been determined that aluminum-based sheet materials have been subjected to fewer studies on roughness transfer by rolling. It has been observed that AA2024-T3 alloy materials, which are used extensively in the aerospace and automotive fields, have not been subjected to roughness transfer in cold rolling and there is a gap in this subject. In this study, AA2024-T3 aluminum alloys were subjected to cold rolling process using roughened rolls at different reduction ratios. The roughness transfer to the material with different reduction ratios was experimentally investigated.

Materials and Methods

Material

In this study, AA2024-T3 aluminum alloys were preferred. AA2024-T3 aluminum alloys are frequently used in aerospace structural components due to their many advantages such as high strength, corrosion resistance and easy machinability. The chemical composition of AA2024-T3 aluminum alloy is given in Table 1 and its mechanical properties are given in Table 2. 2 mm thick AA2024-T3 aluminum alloys were prepared using a 125 mm long, 25 mm wide laser cutting machine. The surfaces of the cut samples were cleaned with ethyl alcohol and subjected to rolling tests.

Table 1. Chemical composition of AA2024-T3 aluminum alloy sheet material [22].

Chemical composition (wt%)								
Al	**Cu**	**Mg**	**Mn**	**Fe**	**Zn**	**Si**	**Ti**	**Cr**
Balance	4.55	1.49	0.45	0.17	0.16	0.10	0.02	<0.01

Table 2. Mechanical properties of AA2024-T3 aluminum alloy material [23, 24].

Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain (mm/mm)
72.4	345.0	482.0	0.1587

Methods

Rolling tests were carried out in the rolling test equipment by setting four different reduction ratios (1%, 5%, 10%, 20%). The reduction ratios were determined by the ratio of the difference between the thicknesses of the material before the rolling process and the thicknesses after the rolling process to the thicknesses before the rolling process. Rolling tests were carried out under dry conditions with 75 mm diameter rough rolls at a rolling speed of 10 rpm. Rolling loads were read from the load cell during each test. After the rolling tests, the roughness measurements of the surfaces were performed using a PCE-RT 2000 roughness tester and the surfaces were imaged with a SOIF XJP-6A optical microscope at 10X magnification. Figure 1 shows the rolling test equipment and characterization methods used in the study.

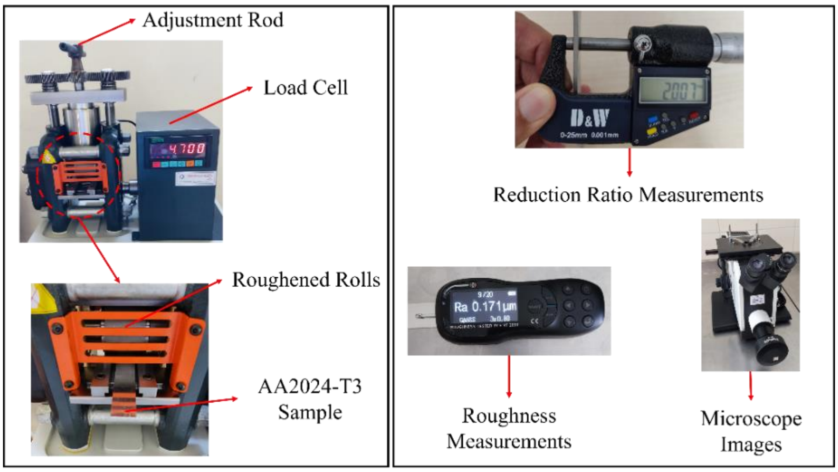

Figure 1. Rolling test equipment and characterization methods.

In order to ensure roughness transfer, the rolls were manufactured by roughening with diamond. The average roughness (R_a) of the top and bottom rolls was calculated as 3.4 µm. Roughness measurements of the rolls were performed at four different points from the center points of the rolls and averages were taken. In the roughness measurements of the material surfaces, three measurements were taken from different points in the rolling direction and the roughness parameters of the surfaces were determined.

Within the scope of the study, the roughness transfer ratio (RR) transferred from the rolls to the surfaces of AA2024-T3 aluminum alloy materials was determined using the formula given in Equation 1 [25]. In the equation, R_{a_e} is the arithmetic mean surface roughness after rolling, R_{a_b} is the arithmetic mean surface roughness before rolling and R_{a_r} is the arithmetic mean surface roughness of the roll pairs.

$$RR\ (\%) = \frac{R_{a\_e} - R_{a\_b}}{R_{a\_r} - R_{a\_b}} \times 100 \qquad (1)$$

Results and Discussion

Roughness transfer was performed on AA2024-T3 aluminum alloys by cold rolling process at different reduction ratios and the thicknesses of the materials were measured with a micrometer. The photos of aluminum samples before and after rolling with several reductions are given in Figure 2. In these images, the load values read from the load meter during roughness transfer in the cold rolling process were also written. The average values of thicknesses measured at three different points after each pass are given in Table 3. Material thicknesses for each pass initial thickness is 2.02 mm.

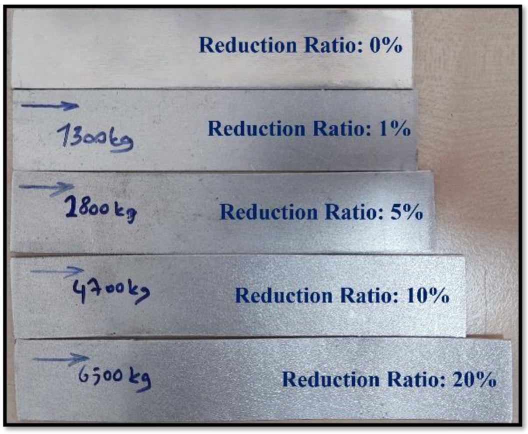

Figure 2. Images obtained from samples roughened by cold rolling.

Table 3. Material thicknesses of AA2024-T3 aluminum alloys before and after roughness transfer by cold rolling

Reduction Ratio (%)	Thickness (Average)
0	2.02
1	2.00
5	1.92
10	1.82
20	1.62

After roughness transfer to AA2024-T3 aluminum alloys by cold rolling, the roughness parameters R_a (arithmetic mean roughness), R_p (maximum profile peak height) and R_v (maximum profile valley depth) of the surfaces were measured and the graph showing the relationship between these parameters and reduction ratios is given in Figure 3. The R_a parameter increases with increasing reduction ratio. When the reduction ratio increased from 1% to 5%, the R_a parameter increased by 52%. When the reduction ratio increased from 5% to 20%, the R_a parameter increased by 42%. It is seen that the increasing trend in the R_a at reduction ratios of 5% and more is less compared to the Ra in the 0%-5% reduction ratio range. It can be said that the onset of work hardening in the material at high reduction ratios, and thus it prevents the roughness transfer from the roll to the material. This is also stated in the literature [26].

It is also possible to see that the increasing trend of R_v and R_p parameters with the increase in the reduction ratio exhibits a similar behavior to the R_a parameter. When the reduction ratio increased from 1% to 5%, the R_v parameter increased by 44%. When the reduction ratio increased from 5% to 20%, the R_v parameter increased by 14%. Likewise, when the reduction ratio increased from 1% to 5%, the R_p parameter increased by 114%. When the reduction ratio increased from 5% to 20%, the R_p parameter increased by 90%. This shows that with increasing reduction ratio, the roll roughness peaks and valleys are transferred to the material to a lesser extent due to the hardening of the material and forward slip during rolling.

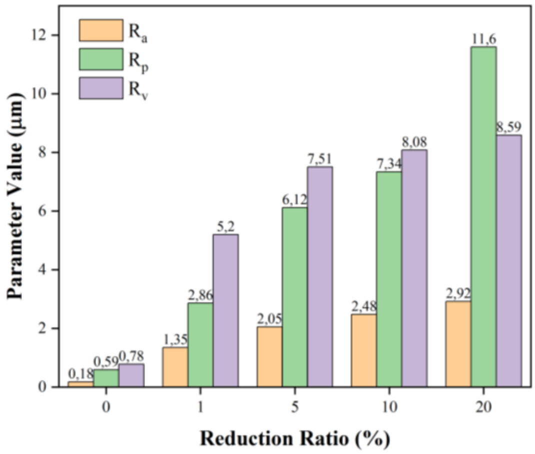

Figure 3. Relationship between reduction ratio and roughness parameters R_a, R_p and R_v.

After roughness measurements were made on the samples, roughness transfer ratios were calculated using Equation 1. The relationship between different reduction ratios and roughness transfer ratios is shown in Figure 4. It is seen that the roughness transfer ratio increases with increasing reduction ratio. When the reduction ratio increased from 1% to 5%, the roughness transfer ratio increased by 61%. When the reduction ratio increased from 5% to 20%, the roughness transfer ratio increased by 47%. The reduction ratio is one of the most effective parameters in the roughening process and it is frequently found in literature that the roughness transfer ratio increases as the reduction ratio increases [27, 28]. With increasing reduction ratio, the peaks and valleys on the roll surface are effectively transferred to aluminum sheet materials. Thus, the material surface gets closer to resembling the roughness profile of the roll. Although this ratio is predicted to be 100% due to the forward shift in rolling behavior, this is impossible in practice. However, it can be said that the work hardening, and forward slip behavior of the material have a great effect on this situation.

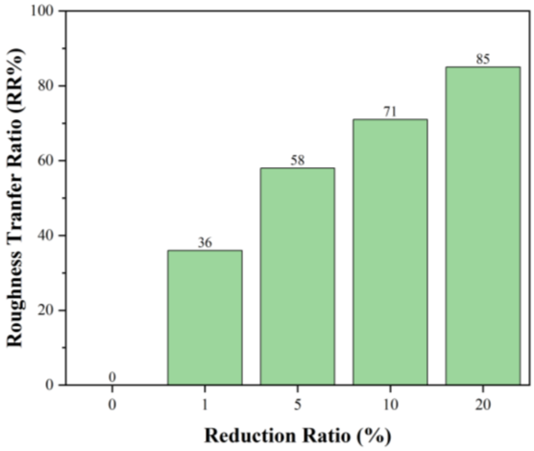

Figure 4. Relationship between different reduction ratios and roughness transfer ratios.

Specific roll force (rolling forces acting on unit length) were calculated from the load values. The graph showing the relationship between different reduction ratios and rolling forces is shown in Figure 5. It is seen that the rolling force increases with increasing reduction ratio. The findings agree with the literature studies [29]. When the reduction ratio increased from 1% to 5%, the rolling force increased by 115%. When the reduction ratio increased from 5% to 20%, the rolling force increased by 132%. At higher reduction ratios, higher rolling forces occur due to the increased volume of material that must be formed in a given time and the onset of work hardening. This means a shorter roll life and higher wear rates. Determining the appropriate parameters that can provide ideal roughness transfer will provide many advantages such as roll life and energy consumption.

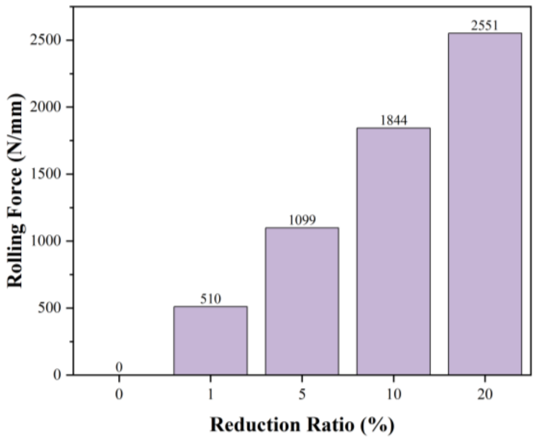

Figure 5. Relationship between different reduction ratios and rolling forces.

The roughness profiles on the sample surfaces that were obtained with different reduction ratios are shown in Figure 6. It is seen that in the roughness transfer process by cold rolling at 1% reduction ratio, the peak and valley distributions of the roughness profile exhibit a homogeneous distribution in the range of approximately ±5 µm. In the roughness transfer process with cold rolling at 5% and higher reduction ratios, it is seen that the homogeneous distribution of peaks and valleys in the roughness profile starts to deteriorate. This is indicated by the irregular fluctuation of the intense peaks and valleys. Based on the findings, we can say that high reduction rates (>1%) hurt the homogeneous distribution of the roughness profile. It should be noted that homogeneous roughness distribution is very effective in terms of dyeing and shaping [30].

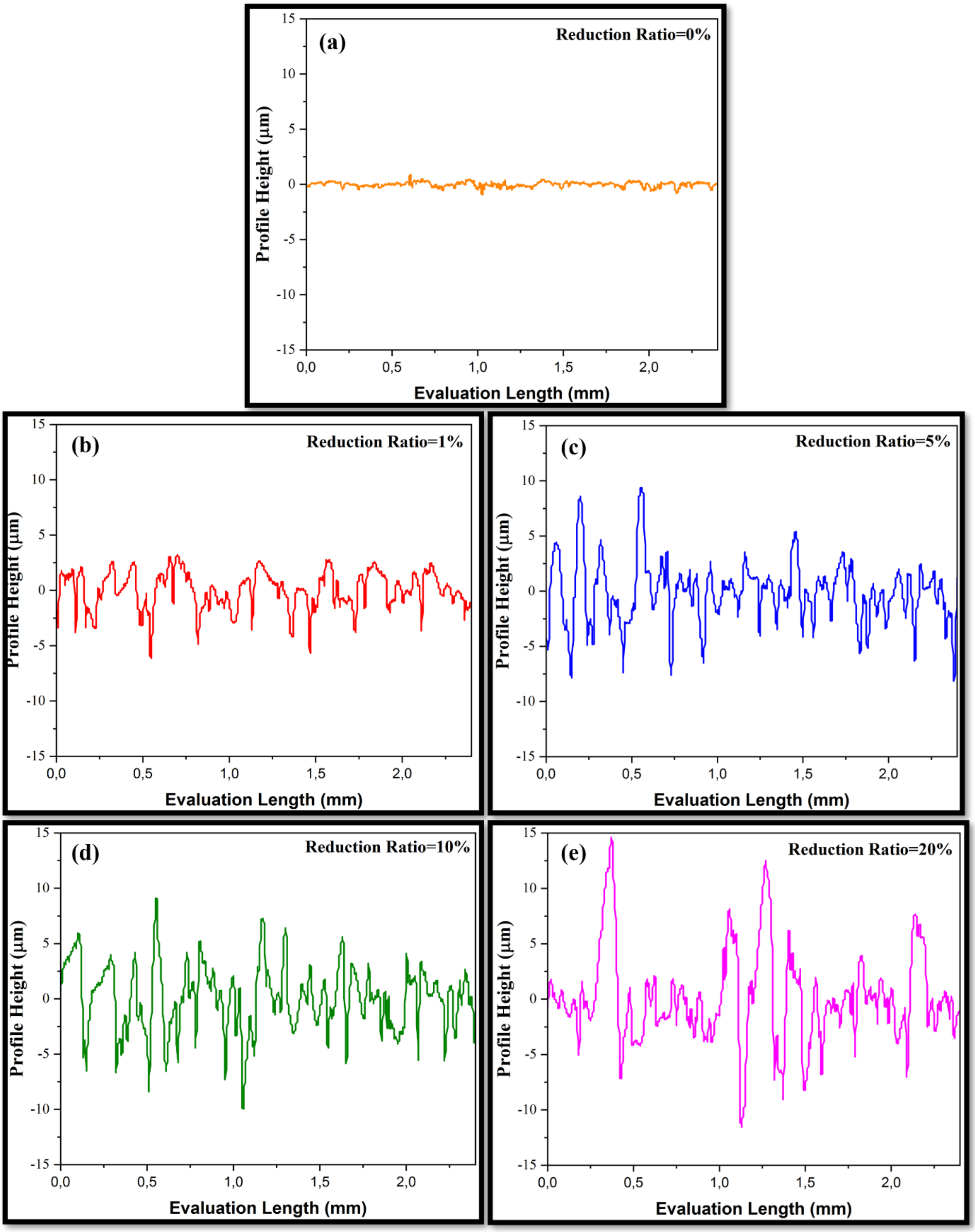

Figure 6. Roughness profiles of materials in the roughness transfer process by cold rolling at different reduction ratios.

Microscope images of the material surfaces of AA2024-T3 aluminum alloys in the roughness transfer process by cold rolling at different reduction ratios are shown in Figure 7.

In the roughness transfer process by cold rolling at 1% reduction rate, the traces formed on the material surface are in a certain order and the dark-colored regions represent the valleys transferred from the rolls to the sheet material surface. In the roughness transfer process with cold rolling at 5% and higher reduction ratios, the dark colored regions in the traces formed on the surface of the material increase, but it is observed that the density of valleys and peaks gradually increases compared to 1% reduction ratio. The increase in valleys, peaks, and irregular craters on the surface reveals that the homogeneous distribution of valleys and peaks on the material surface is disrupted.

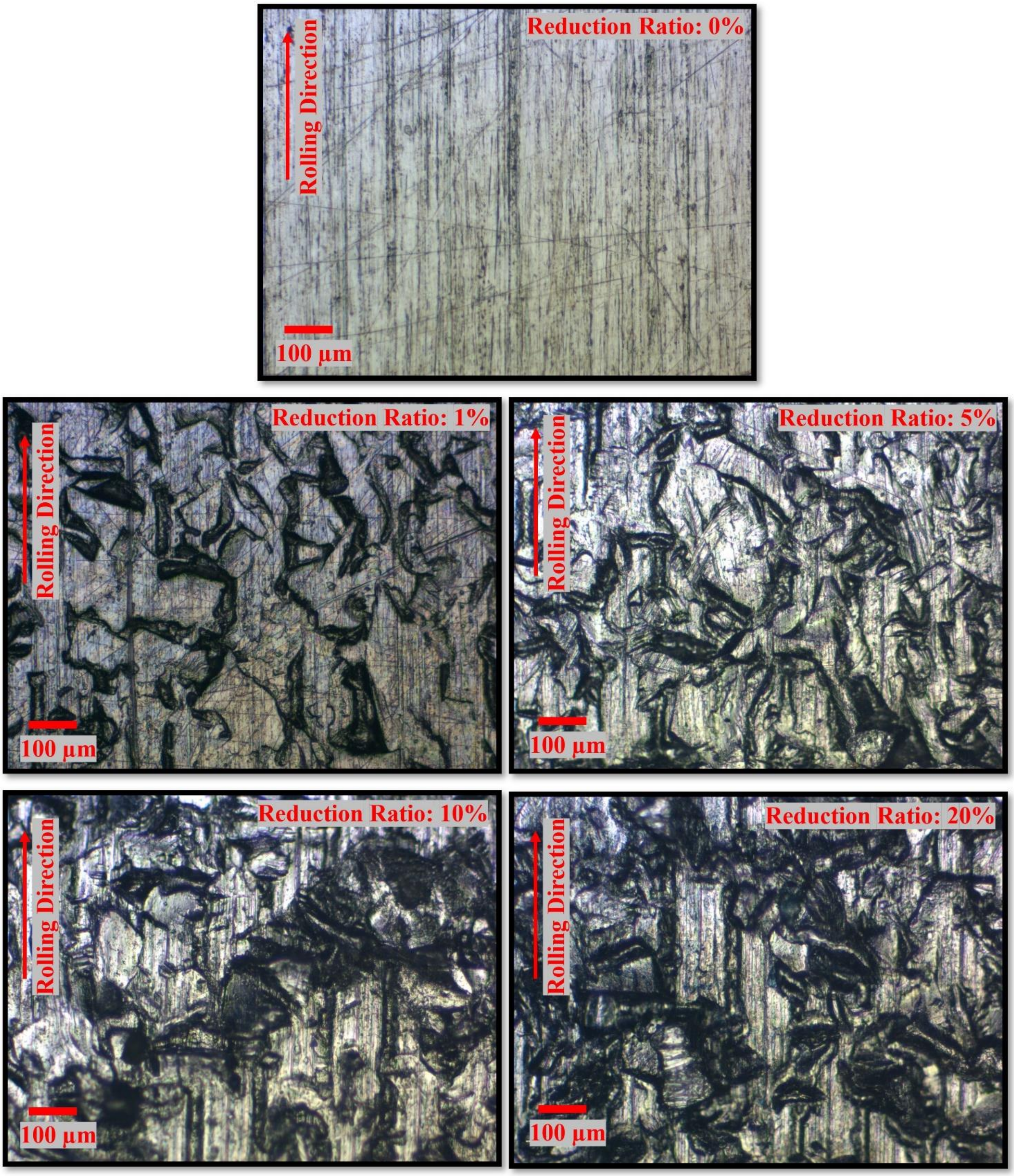

Figure 7. Microscope images of materials in the roughness transfer process by cold rolling at different reduction ratios.

Conclusion

In this study, AA2024-T3 aluminum alloys were subjected to a roughness transfer process with different reduction ratios. In the study, roughness profiles, parameters and images transferred to the surfaces of AA2024-T3 aluminum alloys due to the rolling process were evaluated and roughness transfer behaviors transferred to the material with different reduction ratios were tried to be determined. The results obtained from the study are given below.

- It was determined that the increased tendency in R_a, R_p and R_v roughness parameters at reduction ratios of 5% and above was less compared to R_a, R_p and R_v roughness parameters in the reduction ratio range of 0%-5%.
- As the reduction ratio increased, the roughness transfer ratio increased. This increase was determined to be 61% when the reduction ratio increased from 1% to 5% and 47% when it increased from 5% to 20%.
- The rolling force increased with an increasing reduction ratio. This increase was 115% when the reduction ratio increased from 1% to 5% and 132% when the reduction ratio increased from 5% to 20%.
- It was concluded that the roughness profile exhibited homogeneous distribution in terms of peak, valley distributions, and surface images in the roughness transfer process by cold rolling at a 1% reduction ratio, and the homogeneous distribution deteriorated at reduction ratios of 5% and above.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

The contribution of the authors is equal.

References

[1] X. Li, C. Schulte, D. Abel, M. Teller, G. Hirt, and J. Lohmar, J, "Modeling and exploiting the strip tension influence on surface imprinting during temper rolling of cold-rolled steel," *Advances in Industrial and Manufacturing Engineering*, 3, 100045, 2021.

[2] B. Çolak, and N. Kurgan, "An experimental investigation into roughness transfer in skin-pass rolling of steel strips," *The International Journal of Advanced Manufacturing Technology*, 96, 3321-3330, 2018.

[3] B. Özakın, and Kurgan, N, "Experimental investigation of roughness transfer with skin-pass rolling to high strength low alloy (HSLA) material," *Arabian Journal for Science and Engineering*, 46(12), 12137-12144, 2021.

[4] M. A. Mekicha, M. B. De Rooij, L. Jacobs, D. T. A. Matthews, and D. J. Schipper, "Experimental validation of contact models for cold-rolling processes," *Journal of Materials Processing Technology*, 275, 116371, 2020.

[5] E. Rodriguez-Vidal, D. T. A. Matthews, V. S. de Viteri, F. Korver, D. J. Wentink, and I. Quintana, "Surface design and texturing of strip steel using nanosecond pulsed lasers for simulated roughness transfer and paint appearance," *Journal of Materials Processing Technology*, 275, 116365, 2020.

[6] B. Özakın, and N. Kurgan, "DC04 kalite sac malzemelere temper haddeleme ile pürüzlülük transferinde yağlayıcının etkisinin incelenmesi," *Uluslararası Doğu Anadolu Fen Mühendislik ve Tasarım Dergisi*, 2(2), 325-336, 2020.

[7] B. Özakın, B. Çolak, and N. Kurgan, "Effect of material thickness and reduction ratio on roughness transfer in skin-pass rolling to DC04 grade sheet materials," *Industrial Lubrication and Tribology*, 73(4), 676-682, 2021.

[8] C. Wu, L. Zhang, P. Qu, S. Li, and Z. Jiang, "Effect of the elastic deformation of rolls on the surface texture transfer in skin-pass rolling," *International Journal of Mechanical Sciences*, 198, 106358, 2021.

[9] A. Patel, A. Malik, F. Zhang, and R. Mathews, "Influence of work-roll grinding error and high-fidelity corrective grinding in cold sheet rolling," *The International Journal of Advanced Manufacturing Technology*, 120(11), 7389-7413, 2022.

[10] Z. Zhang, H. Zhang, X. Liu, T. Wang, Q. Huang, and X. Liao, "Effect of roll surface topography on microstructure and mechanical properties of 304 stainless steel ultra-thin strip," *Journal of Manufacturing Processes*, 108, 764-778, 2023.

[11] R. Matin, Y. Totik, E. E. Sukuroglu, I. Efeoglu, and T. G. Santos, "Effects of voltage on the components of surface integrity of Al2O3 ceramic coatings on AA2024 by plasma electrolytic oxidation," *Journal of Adhesion Science and Technology*, 34(18), 1971-1981, 2020.

[12] H. I. Yurdgulu, R. Sadeler, H. Yilmaz, and B. Koc, "Corrosion fatigue behavior of AA 7020 alloy in seawater," *Materials Testing*, 65(5), 743-752, 2023.

[13] S. S. Li, X. Yue, Q. Y. Li, H. L. Peng, B. X. Dong, T. S. Liu, H. Y. Yang, J. Fan, S. L. Shu, F. Qiu, and Q. C. Jiang, "Development and applications of aluminum alloys for aerospace industry," *Journal of Materials Research and Technology*, 27, 944-983, 2023.

[14] O. A. Gali, M. Shafiei, J. A. Hunter, and A. R. Riahi, "The influence of work roll roughness on the surface/near-surface microstructure evolution of hot rolled aluminum–magnesium alloys," *Journal of Materials Processing Technology*, 237, 331-341, 2016.

[15] J. G. Lenard, "The effect of roll roughness on the rolling parameters during cold rolling of an aluminum

alloy," *Journal of Materials Processing Technology*, 152(2), 144-153, 2004.

[16] M. F. Frolish, M. Krzyzanowski, W. M. Rainforth, and J. H. Beynon, "Oxide scale behaviour on aluminium and steel under hot working conditions," *Journal of Materials Processing Technology*, 177(1-3), 36-40, 2006.

[17] J. Sun, H. Ying, and M. Lu, "Optimize aluminum's surface roughness in rolling lubrication process," *Industrial Lubrication and Tribology*, 65(3), 175-180, 2013.

[18] Y. R. Jeng, J. T. Lee, Y. J. Hwu, L. C. Liu, and C. Y. Lu, "Effects of operation parameters of cold rolling on surface finish of aluminum," *Tribology International*, 148, 106321, 2020.

[19] E. A. Hussein, J. Gattmah, A. N. Jaseem, and S. K. Shibab "Optimization of rolling parameters for enhancing the surface integrity of aluminum alloy," *Journal of Harbin Institute of Technology (New Series)*, 30(6), 70-82, 2023.

[20] L. Ma, J. Lian, X. Ma, S. Bai, L. Ma, and J. Zhao, "A study on the tribological behavior of water-based nanolubricant during corrugated rolling of copper plates," *The International Journal of Advanced Manufacturing Technology*, 129(3), 1513-1526, 2023.

[21] P. Warneke, A. Bohlen, and T. Seefeld, "Texturing skin-pass rolls by high-speed laser melt injection, laser ablation, and electrolytic etching," *Journal of Laser Applications*, 36(1), 012011, 2024.

[22] N.M. André, S. M. Goushegir, J. F. Dos Santos, L. B. Canto, and S. T. Amancio-Filho, "Friction Spot Joining of aluminum alloy 2024-T3 and carbon-fiber-reinforced poly (phenylene sulfide) laminate with additional PPS film interlayer: Microstructure, mechanical strength and failure mechanisms," *Composites Part B: Engineering*, 94, 197-208, 2016.

[23] S. Akpinar, M. D. Aydin, and A. Özel, "A study on 3-D stress distributions in the bi-adhesively bonded T-joints," *Applied Mathematical Modelling*, 37(24), 10220-10230, 2013.

[24] K. Gültekin, and Y. Korkmaz, "AA2024-T3 alüminyum alaşımlarına uygulanan farklı yüzey hazırlama ve pürüzlülük işlemlerinin yapıştırma bağlantılarına etkisi," *Gümüşhane Üniversitesi Fen Bilimleri Dergisi*, 11(4), 1269-1281, 2021.

[25] H. Kijima, "Influence of roll radius on roughness transfer in skin-pass rolling of steel strip," *Journal of Materials Processing Technology*, 214(5): 1111-1119, 2014.

[26] C. Wu, L. Zhang, P. Qu, S. Li, and Z. Jiang, "A new method for predicting the three-dimensional surface texture transfer in the skin pass rolling of metal strips," *Wear*, 426, 1246-1264, 2019.

[27] D. Xu, Q. Yang, X. Wang, H. He, Y. Sun, and W. Li, "An experimental investigation of steel surface topography transfer by cold rolling," *Micromachines*, 11(10), 916, 2020.

[28] B. Özakin, "Experimental investigation of the effect of skin-pass rolling reduction ratio on corrosion behaviors of AISI 304 stainless steel sheet materials," *Surface Topography: Metrology and Properties*, 11(2), 025004, 2023.

[29] B. Çolak, Z. Ahmed, B. Özakın, and N. Kurgan, "An experimental investigation into roughness transfer in asymmetrical rolling of steel strips," *Karadeniz Fen Bilimleri Dergisi*, 13(3), 1070-1089,2023.

[30] B. Özakın, and E. Yılmaz, "Sac malzemelerin boyanabilme kabiliyetlerine temper haddeleme ezme miktarının etkisi," *Karadeniz Fen Bilimleri Dergisi*, 13(2), 517-530, 2023.