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Araştırma Makalesi / Research Article

An Experimental Investigation into Roughness Transfer in Asymmetrical Rolling of Steel Strips

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Abstract

This study investigated the effect of rolling parameters such as speed, thickness reduction, roll surface roughness, material thickness, surface condition (dry or lubricated), and rolling force on the roughening characterization in asymmetrical rolling. The surface roughness of the samples subjected to rolling tests was measured. The roughness values' average and standard deviation were found, and 3-D scanning images were acquired. Lubricated texturing experiments revealed that lubrication reduced roughness transfer. It was found that the introduction of roughness on the material surface decreased as the rolling speed increased. On the other hand, a higher speed increases the rolling force, which increases the surface roughness. The effect of speed on the standard deviation varies in direct proportion. Furthermore, lubricated rolling produced a more homogenous roughness distribution at higher speeds, while dry rolling produced homogeneous roughness at lower speeds. It was revealed that the rolling force is higher with thicker materials. While the roll roughness did not affect the rolling force using thicker material much, this effect was more pronounced in the very rough roll using thinner material. The standard deviation was lower in smaller reduction ratios using rough and very rough rolls. According to the results, although asymmetrical rolling has some advantages compared to conventional rolling, it was concluded that it is not a suitable method for roughening steel strips.

Keywords: Asymmetrical rolling, Homogeneous roughness, Rolling force, Rolling speed, Roll roughness, Roughness (transfer).

Çelik Sacların Asimetrik Haddelenmesinde Pürüzlülük Transferinin Deneysel Olarak İncelenmesi

Öz

Bu çalışmada asimetrik haddelemede hız, kalınlık azalması, merdane yüzey pürüzlülüğü, malzeme kalınlığı, yüzey durumu (kuru veya yağlanmış) ve haddeleme kuvveti gibi haddeleme parametrelerinin pürüzlendirme karakterizasyonu üzerindeki etkisi incelenmiştir. Haddeleme testine tabi tutulan numunelerin yüzey pürüzlülükleri ölçülmüştür. Pürüzlülük değerlerinin ortalaması ve standart sapması belirlenerek 3 boyutlu tarama görüntüleri elde edilmiştir. Yağlanmış pürüzlendirme deneyleri, yağlamanın pürüzlülük transferini azalttığını ortaya çıkarmıştır. Haddeleme hızı arttıkça malzeme yüzeyindeki pürüzlülüğün azaldığı bulunmuştur. Öte yandan yüksek hız, yüzey pürüzlülüğünü artıran haddeleme kuvvetini artırıcı bir etkiye sahip olduğu görülmüştür. Hızın standart sapma üzerindeki etkisi doğru orantılı olarak değişmektedir. Ayrıca yağlı haddeleme yüksek hızlarda daha homojen bir pürüzlülük dağılımı sağlarken, kuru haddeleme daha düşük hızlarda homojen bir pürüzlülük vermiştir. Kalın malzemelerle haddeleme kuvvetinin daha yüksek olduğu ortaya çıkmıştır. Kalın malzeme kullanımında merdane pürüzlülüğünün haddeleme kuvvetine fazla etkisi olmazken, ince malzeme kullanımında çok pürüzlü merdanede bu etki daha belirgin olmuştur. Pürüzlü ve çok pürüzlü merdanelerin kullanıldığı küçük ezme oranlarında standart sapmanın daha düşük olduğu görülmüştür. Elde edilen sonuçlara göre asimetrik haddelemenin geleneksel haddelemeye göre bazı avantajları olmasına rağmen çelik sacların pürüzlendirilmesi için uygun bir yöntem olmadığı sonucuna varılmıştır.

Anahtar Kelimeler: Asimetrik haddeleme, Homojen pürüzlülük, Haddeleme kuvveti, Haddeleme hızı, Merdane pürüzlülüğü, Pürüzlülük transferi

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1. Introduction

Surface roughness is critical to giving the sheet its ultimate form. Surface roughness (Ra) is the arithmetic mean of the surface profile's centerline distance. Surface roughness supplies oil pockets on the material surface where mold oil can cling. It is an advantage in terms of shaping as it increases the lubricating property on the contact surface of the sheet and the mold. Despite this, a significant degree of roughness causes the painted surface to seem dull (Elkoca 2008; SMS DEMAG 2003). That is why surface roughness should be in a definite range on the sheet's surface. While surface roughness between 1.0 and 1.5µm is preferred in the outer body parts of automobiles, higher roughness is desired in the interior parts (Thyssen Krupp Stahl 2004).

Many factors influence roughness transfer in rolling. It was discovered that roughness transfer increased with elongation (Kimura, Ueno, and Mihara 2009). The SMS Group achieved equivalent results as Kimura, and this increase in roughness transfer was more pronounced in thinner materials (SMS DEMAG 2003). Kijima conducted dry and lubricated testing with 50- and 250-mm-radius rolls and found results comparable to the SMS group (Kijima 2015). Kijima, in another study, revealed the effect of rolling force on roughness transfer. He conducted conventional rolling (acronym CR) experiments using two radii of rolls with different surface roughnesses. He revealed that the transfer ratio increased as the rolling force increased for both roughnesses (Kijima 2014). Wentink reached similar results and proved this result via microscopic images (Wentink et al. 2015). The findings of Çolak and Kurgan also show parallelism with this result (Çolak and Kurgan 2018). It has been found that the transfer rate increased with the reduction ratio, but the rolling speed did not have a dramatic effect (Özakın and Kurgan 2021; Wu et al. 2019). Xu et al. found that the strip surface topography increasingly became the same as the roll surface topography as the reduction ratio increased (Xu et al. 2020). On the other hand, Wu et al. stated that the entire transfer (100%) of surface roughness was impossible, and almost no roughness was obtained on the rolled material surface at minimal reduction ratios due to elastic deformation (Wu et al. 2018). Li et al. obtained a surface roughness in a narrower range in simulating a two-stand skin-pass rolling mill which has the second-stand roll roughness being lower than the first one (Li et al. 2015). Wu et al. revealed that as roughened work rolls wear, surface texture transfer to the rolled sheet decreases gradually (Wu et al. 2021).

Homogeneous distribution on the material surface is as vital as the roughness level. Studies investigating the effect of rolling parameters on roughness found that lubrication, slight reduction, low speed, and low roll roughness reduced transfer but increased homogeneity (Çolak and Kurgan 2018; Özakın, Çolak, and Kurgan 2021; Özakın and Kurgan 2021). The rolling factors impact not only the surface roughness of the material and the rolls but also the surface topographical orientation of the rolls. To minimize extra tensile stresses that may induce ripping in the strip width direction, Mazur reasoned that the surface micro-relief should be consistent along the roll-barrel axis (Mazur 2015).

The surface roughness is imparted by conventional cold rolling (CR) with textured rolls. Although many studies have been published on roughening by CR and the effects of process parameters in AR on microstructure, grain refinement, crystallographic orientation, rolling force, mechanical behaviour, and texture evolution, studies regarding AR texturing have yet to be conducted. This study aims to determine whether surface roughening can be done with asymmetrical rolling and how the rolling parameters affect the result.

2. The Principles of Asymmetrical Rolling

Mechanical properties are in good balance in materials with heterogeneous microstructures (formation of plastic gradients) (Muñoz et al. 2021). Asymmetrical rolling (acronym AR) is an effective method to create heterogeneous microstructure in the material. Due to the asymmetry and this heterogeneous structure, there is no deterioration in the strip profile but an improvement (Vincze, Simões, and Butuc 2020). In the CR process, which is a symmetrical rolling (Fig 1a), until the neutral point, the tangential friction force act in the direction to draw the material into the roll. After the neutral point, the frictional force's direction is reversed and opposes the delivery of the sheet from the rolls (Beddoes and Bibby 1999). Since the neutral points of both rolls are on the same vertical plane due to the symmetry, as shown in Fig 1a, the direction of tangential frictional force is always the same in all vertical planes through the roll gap for both rolls. In this way, the material would flow through the roll gap with a symmetric deformation texture (Fig 1c).

AR conditions can be produced using rolls of varying radii, rotation speeds, or surface conditions. Because of this asymmetry, the sheet tends to bend. With a smaller diameter top roll, the neutral points are no longer on the same vertical plane. The neutral point of the small roll (top roll) shifts toward the entry side, while the neutral point of the larger roll (bottom roll) shifts toward the exit side, and the sheet tends to bend due to this asymmetry (Fig 1b). In the region between the neutral points, the frictional forces acting in opposite directions on both surfaces and the greater sliding distance cause a heterogeneous and more significant shear deformation through the thickness of the material in AR. Vincze et al. stated that the roll diameters (asymmetry ratio) ratio is 1.5 to create uniform shear deformation across the thickness and decrease normal pressure (Vincze et al. 2020). Wauthier et al. reported various thickness reductions (32.2-36.8%) in the tests with different asymmetry ratios (1.10-1.45), although the gap between the rolls and the roll surface roughness is the same (Wauthier et al. 2009). This introduced shear strain changes the deformation stream and microstructure evolution (Fig 1d). In CR, texture twist only occurs in the surface zones, while in AR, it occurs in the central region throughout the thickness of the material. Thanks to these properties in AR, finer microstructure, improved mechanical behavior, and highly formable material can be obtained. Munoz et al. compared low-carbon steel subjected to AR after cold rolling regarding texture evolution, strain path heterogeneity, microstructure, and mechanical properties. They stated that AR applied after CR for the same thickness reduction enhances material strength (Muñoz et al. 2021). Cho et al. also reached similar conclusions in their research. They revealed that AR applied after CR reduces basal texture density and improves mechanical properties (Cho et al. 2013). Also, a lower rolling force by almost half and lower torque is another advantage of AR compared to CR (Fajfar et al. 2017; Kiefer and Kugi 2008; Liu and Kawalla 2012; Orlov et al. 2013; Vincze et al. 2020). Moreover, it is possible to get thinner material in AR with the same gap between the rolls comparing the CR process (Vincze et al. 2020).

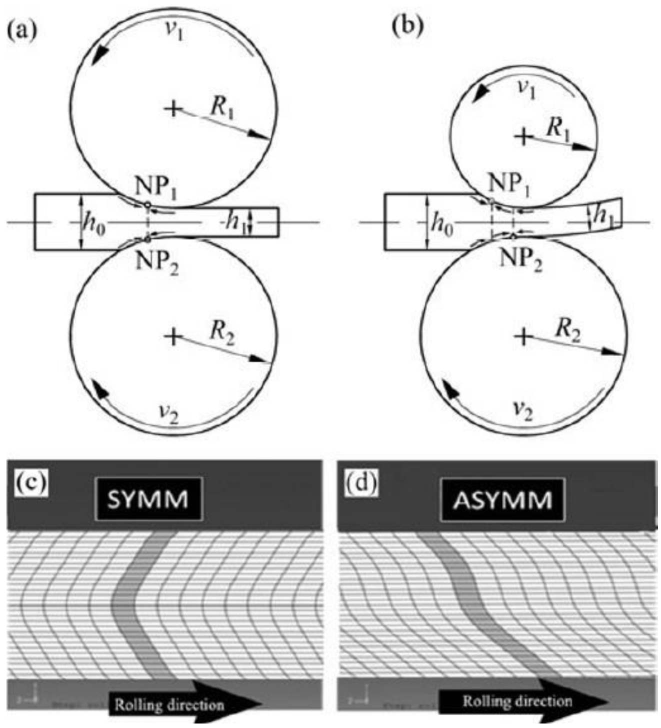


Figure 1. Schematic illustrations **a)** Symmetric rolling (R1=R2, V1=V2) **b)** Asymmetric rolling (R1<R2, V1<V2) **c)** Shear deformation texture through the thickness in CR **d)** Heterogeneous shear deformation texture through the thickness in AR (Liu & Kawalla, 2012).

Curvature tendency can be reduced by adjusting the thickness reduction (Kiefer and Kugi 2008). According to their mathematical and computer modeling, the closer the shape factor, calculated by the ratio of contact arc length to average thickness in asymmetric rolling, is to 1.8, the straighter the material will come out. Material curvature in AR can also be eliminated by equipping the rolling mill with a table roller (Fajfar et al. 2017; Kiefer and Kugi 2008). The difference in rolls' speeds and the percentage of thickness reduction affect the curvature tendency. The solution suggestion is small reductions per pass rather than a higher final reduction (Muñoz et al. 2021). The material curvature, which occurred during AR, is shown in Figure 2a. In our tests, the curvature effect of AR is much more pronounced at lower speeds. It is seen that much less curvature occurs in the sample rolled at 50 rpm than in the sample rolled at 10 rpm (Fig. 2b). On the other hand, curvature in the asymmetric rolled sheet may be advantageous during coiling in a down-coiler (Vincze et al. 2020).

a) Curvature occurred during AR. **b)** The speed effect on material curvature.

Figure 2. Material curvature

The surface roughness of the sheet is imparted mainly by conventional cold rolling (CR) with textured rolls. As shown above, many studies have been published on process parameters in AR and their effects on microstructure, grain refinement, crystallographic orientation, rolling force, mechanical behaviour, and texture evolution. However, there needs to be more research on roughness transfer in AR. The study aims to clarify the rolling variables' impact on the AR transfer ratio and compare it with the CR results.

3. Experimental Procedure

3.1. Test Equipment and Material

Rolling tests were performed with a 2-high rolling configuration that allows the speed to be varied from 5 to 100rpm equipped with a 100-ton-capacity load cell to measure the rolling force accurately. The tests were conducted with three rolls, one bright but the others roughened in different values (Table 1). The top roll was roughened, but a bright and larger roll was used as the bottom roll to produce AR conditions. The samples in two different thicknesses were cut to be 30mm wide and 200mm long, and their properties as seen in Table 2.

Table 1. Rolling rolls

	Roll diameter (mm)	Barrel Length (mm)	Surface Roughness (μm)[a]	Surface Hardness (HRC)	Surface condition	Roll material
Rough roll	68	60	3.8	60	Roughened with laser	Cold work tool steel (2379)
Very rough roll	68	60	8.0	60	Roughened with laser	Cold work tool steel (2379)
Bright roll	75	60	Less than 0.4	60	Ground	Cold work tool steel (2379)

Table 2. Material properties

Standard	Grade	Erdemir Grade	Thickness (mm)	Yield Strength (N/mm²)	Tensile Strength (N/mm²)	Elongation (%)	Surface Roughness (μm)*
DIN-EN 10130-2006	DC01	ERD6112	0.73	236.3	339.3	36	1.123
			2.00				

3.2 Rolling Experiments

Rolling tests were performed in lubricated and dry conditions at various thickness reductions and speeds, using different thicknesses of materials and different roughness rolls. Table 3 shows the indication of these parameters. According to the presentation in this table, the 2.0/VR/10/HR/D test indicates 2.0mm material thickness, 8.0μm roll surface roughness (VR), 10rpm speed, higher reduction ratio (HR), and dry (D) condition. All tests were performed at room temperature. The surface roughness was measured with a Mitutoyo SJ-201 surface roughness measuring equipment.

Table 3. Rolling parameters

Material thickness	Indicator	0.7	2.0
	Meaning	0.73mm	2.0mm
Roll surface roughness	Indicator	R (Rough)	VR (Very Rough)
	Meaning	3.8 μm	8.0 μm
Speed	Indicator	10	50
	Meaning	10 rpm	50 rpm
Thickness Reduction	Indicator	SR	HR
	Meaning	Smaller Reduction (100 μm)	Higher Reduction (200 μm)
Surface condition	Indicator	D	L
	Meaning	Dry	Lubricated

The surface roughness of the material should be at a specified level, and the standard deviation should be as low as feasible in white appliances and automobiles body where the surface look is highly essential. By taking at least ten measurements from the rough surface (top surface) of each sample, the standard deviation of the final surface roughness and the standard deviation were calculated, and it was shown the consistency between these results and the 3-D area scan images taken with the Nanovea optical profile measuring device. Scans were performed on a 2 × 2 mm field with an accuracy of 5µm. The obtained results were compared with the results of CR results.

The roughness transfer ratio (RTR) was calculated using Equation (1).

$$RTR[\%] = \frac{Ra_1 - Ra_0}{Ra_r - Ra_0} x100 \quad (1)$$

Ra_0 represents the surface roughness of the material before rolling, Ra_1 represents the surface roughness of the rolled material, and Ra_r represents the roll surface roughness.

4. Results

4.1 The effect of the rolling speed

In roughening tests performed at various speeds (10 rpm and 50 rpm), as long as the other variables are identical, it is seen that the roughness on the material surface is higher at lower speeds (Fig. 3). This is a disadvantage regarding production tonnage when producing materials with high roughness is desired. This may be due to the increased contact time under pressure required for plastic deformation. Qu et al., in their symmetrical rolling tests, explained the situation by flattening the surface asperity as the speed increases, increasing the actual contact area. They also stated that fast-rolling affects this result since it speeds up the progressive shearing process in the contact zone (Qu et al., 2016). However, in the CR study conducted in 2018, the result was the opposite; RTR increased as speed increased (Çolak & Kurgan, 2018).

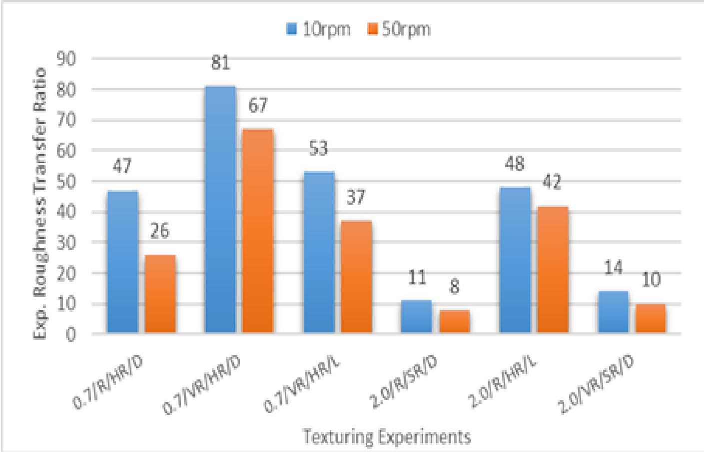


Figure 3. The speed effect on RTR.

4.2 The effect of the lubrication

According to the test results performed by keeping the variables in Table 3 constant, the surface roughness of the dry-rolled material is 14–81 per cent higher than the lubricated one (Fig. 4). This may be because of the increased rolling force due to the higher coefficient of friction in dry rolling (Beddoes & Bibby, 1999). Indeed, experiments found that the roughness transfer increased with the increase of rolling force (Fig. 5). The result is consistent with the previous CR study (Çolak & Kurgan, 2018). The hydrodynamic effect induced at the roll-material contact during lubricated rolling is assumed to be responsible for the poor transfer in both oily symmetric and oily asymmetric rolling.

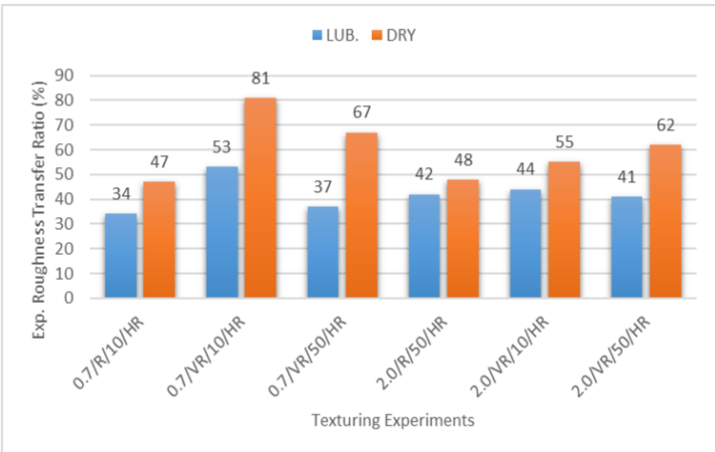


Figure 4. The lubrication effect on RTR

4.3 The Effect of the Rolling Force

4.3.1 Rolling force - roughness transfer relation

The results of thirty-two rolling tests with various parameters given in Table 3 show that the higher the rolling force, the higher the transfer ratio (Fig. 5). It is seen that when the force increases from 1 kN/mm to 3 kN/mm, the transfer increases from 10% to about 50%; that is, the increase in the transfer is greater than the increase in the rolling force. In another study (Çolak & Kurgan, 2018) examining the roughness transfer in symmetrical rolling it was concluded that the transfer ratio was directly proportional to the rolling force, as in this study. The high forces at the exceedingly small contact region between the sharp peaks on the roll surface and the material surface cause the peaks to sink deeper into the material surface, causing deeper craters to form on the material surface. Furthermore, with high loads, lower-height peaks begin to sink into the material surface and contribute to crater formation.

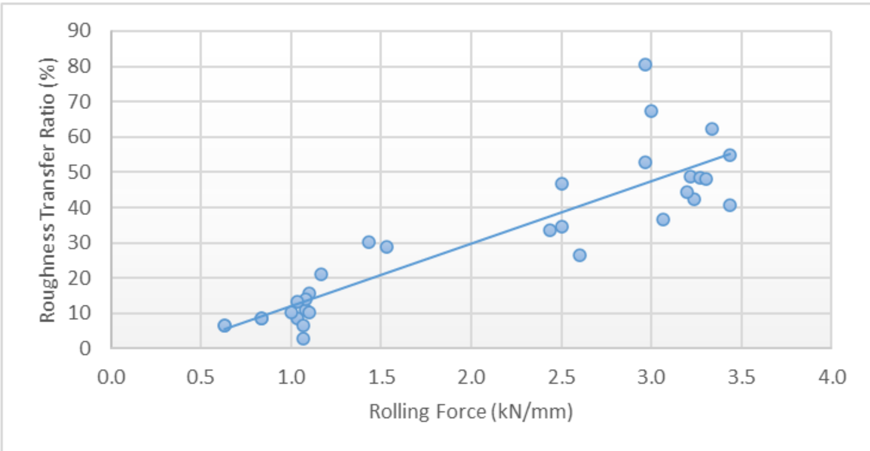


Figure 5. The rolling force effect on RTR

Note: The values under 2kN/mm are for smaller reduction (SR); the values above 2kN/mm are for higher reduction (HR)

4.3.2 Rolling force – material thickness relation

The rolling force is higher in thicker materials under the same conditions in AR (Fig. 6). It may be because in the region between the neutral points, the frictional forces acting in opposite directions on both surfaces and the greater sliding distance cause a heterogeneous and more significant shear deformation through the thickness of the material in AR. Since the rolling force increases the transfer, it should be expected that the roughness transfer is higher in thicker materials. It may be considered an advantage when there needs to be more surface roughness in thicker material during asymmetric rolling. On the other hand, the rolling load was higher in thinner material in the CR process (Fig. 7).

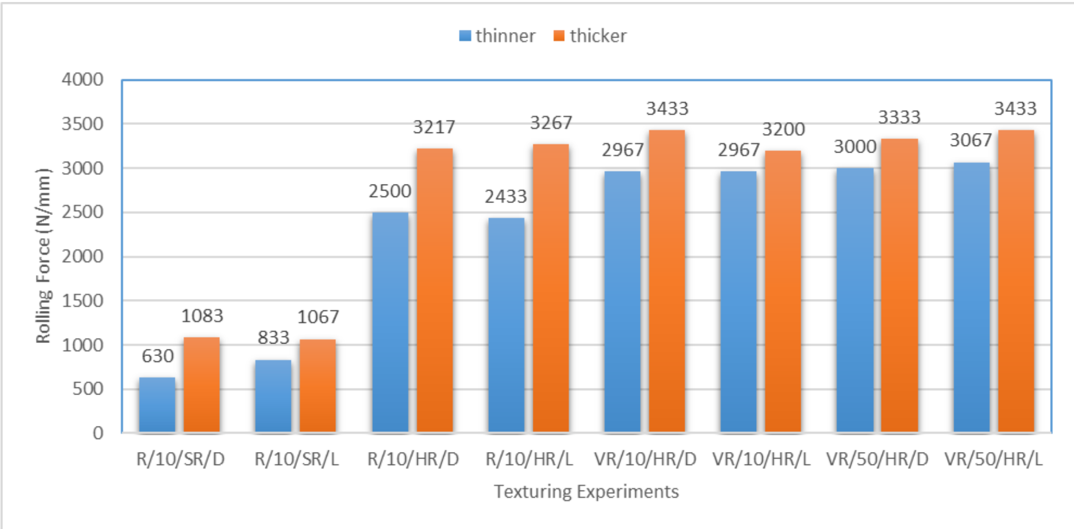


Figure 6. The material thickness effect on rolling force

Rolling occurs under forces of up to two thousand tons, depending on the rolling mill and material properties. Low rolling force means that the rolling system and rolls operate under less load, which means less wear and less cost. According to the literature, one of AR's advantages is the lower rolling load. However, in AR, this benefit only applies to thinner materials. We found that the rolling load is higher in thicker material than the CR results obtained in the previous research (Çolak & Kurgan, 2018). In the CR and AR tests carried out under the same conditions, it is seen that low rolling force occurs in AR with thin material, while low rolling force occurs with thick material in CR (Fig.7).

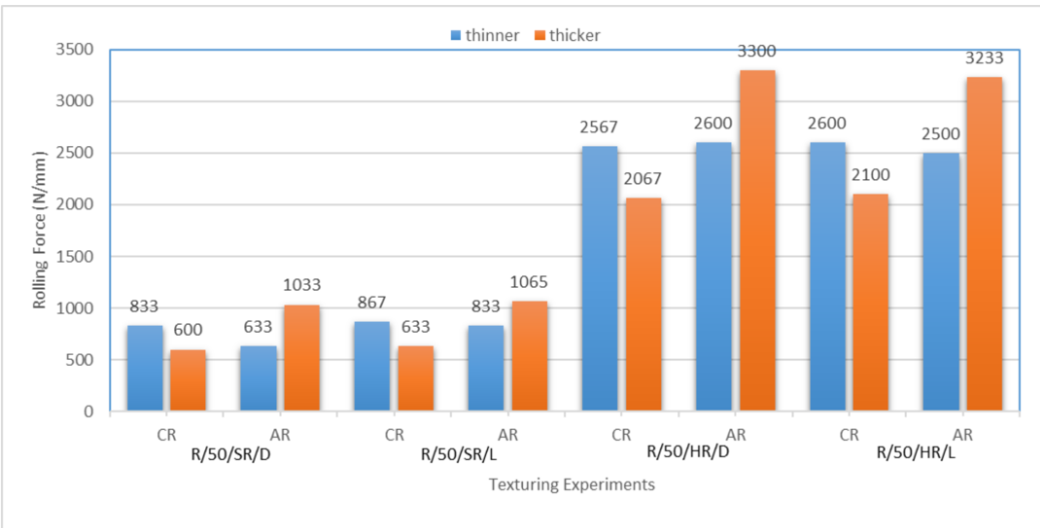


Figure 7. Comparison of rolling force in CR and AR based on material thickness reduction (CR data is taken from the other article (Çolak & Kurgan, 2018))

4.3.3 Rolling force – speed relation

The roughness transfer is larger in AR roughening trials at various speeds (10 and 50 rpm) but with constant roll roughness, reduction ratio, lubrication condition, material thickness, and type (Fig. 8). Although the speed increased five times, the rolling force has a maximum increase of 7%. This relationship and rate are the same as in the other study (Çolak & Kurgan, 2018). Due to the high rolling force concern, this increase in rolling force is not large enough to force the producer to produce at low speeds. The effect of high speeds on increasing the rolling force, which increases the transfer, is another advantage of asymmetric rolling at high speeds. In addition, it is seen that the material tends to curvature less in the AR process performed at high speeds (Fig. 2b).

The sheet is plastically shaped by the force exerted by a pair of opposingly rotating rolls. The increase in the rolling force at high speeds is because, as the speed increases, the volume of material that needs to be plastically shaped per unit of time increases.

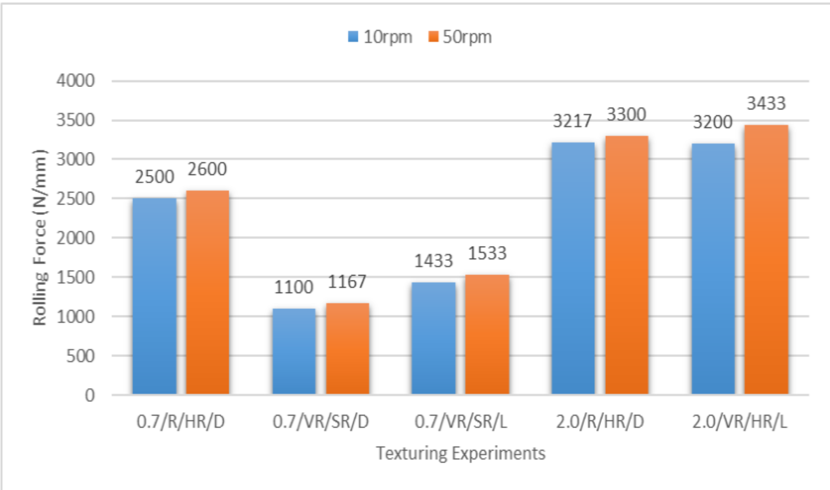


Figure 8. The speed effect on rolling force

4.3.4 Rolling force-roll surface roughness relation

Very rough rolls resulted in greater rolling force than the rough rolls in tests with thinner materials (Fig. 9). Neutral points aren't on the same vertical plane in AR, and the neutral point shifts towards the entry side as friction increases (as roll surface roughness increases) (Fig 1b). In the region between the neutral points, greater sliding distances due to the shifting of neutral points and the frictional forces acting in opposite directions on both sheet surfaces increase the rolling force in AR. This means the transfer will be higher when rolling asymmetrically with very rough rolls. This result agrees with the other research results (Çolak & Kurgan, 2018). However, this is not the case for thicker materials. In the experiments conducted with thicker materials, no meaningful change was observed in the rolling force because of the increase in surface roughness of the roll (Fig. 10).

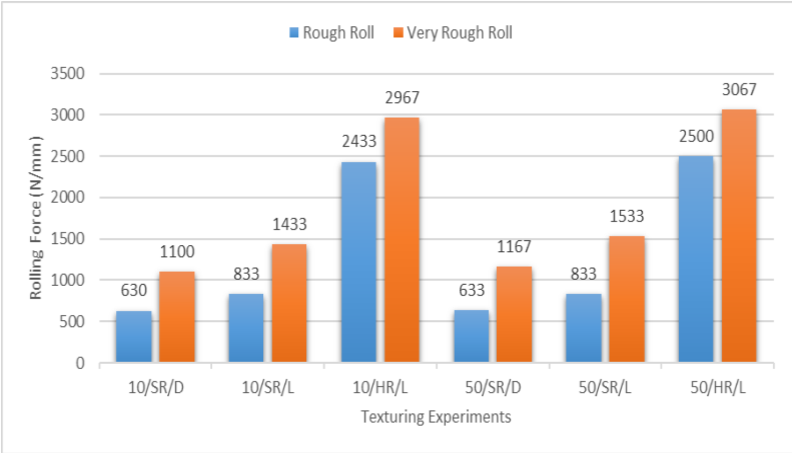


Figure 9. The roll roughness effect on rolling force (for thinner material)

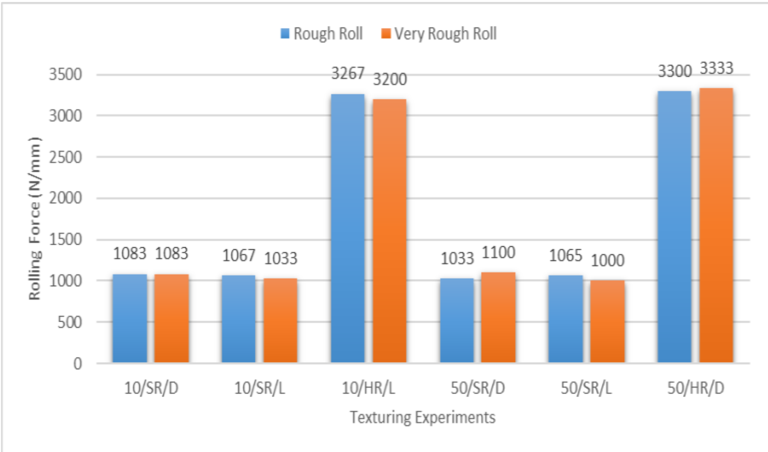


Figure 10. The roll roughness effect on the rolling force (for thicker material)

4.4 Experimental Standard Deviation

The average roughness values (Ra) were calculated by obtaining different measurements from the test samples. Most of the time, more than obtaining this value is required for the appearance quality of the dyed surface. Also, the roughness should vary within a narrow range for the entire surface. Roll surface roughness is vital in imparting these properties to a sheet surface (Çolak, 2021; Çolak & Kurgan, 2018). No matter how homogeneous the roll surface roughness is, it may not be sufficient to get a homogeneous roughness distribution on the material surface. Other parameters affecting this need to be known and controlled. These variables in CR were explored in the previous study, and the situation in AR is as follows.

4.4.1 Reduction ratio effect

When the test findings obtained at a smaller reduction (SR) ratio are compared to those obtained at a higher reduction (HR) ratio, it is seen that a narrower range of roughness distribution is obtained at smaller reduction ratios in the tests performed with rough rolls and very rough rolls (Fig. 11 and Fig. 12). This is also the case with symmetrical rolling (Çolak & Kurgan, 2018). However, it is seen that the standard deviation is higher in the AR rolling tests performed with the very rough roll compared to the symmetrical rolling results (Fig. 13). 3D surface scans were used to visualize this phenomenon. Figures 14a and 14b show 3D surface topographies for the tests performed under 2.0/R/10/SR/L conditions in AR and CR, respectively. After comparison, the symmetrical rolled surface is observed to have a more homogeneous roughness distribution than the asymmetrical rolled surface. The roughness measuring device results from the specimen surface are likewise the same. The standard deviation was 0.08 in CR, while it was measured as 0.15 in AR. It is thought that the friction forces acting in opposite directions on both surfaces in the region between the neutral points in asymmetrical rolling destroy the surface roughness (Fig. 1b).

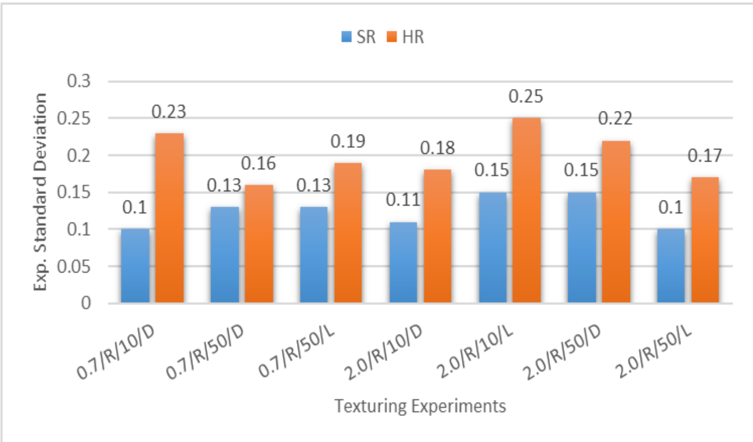


Figure 11. Experimental standard deviation (with rough roll-R)

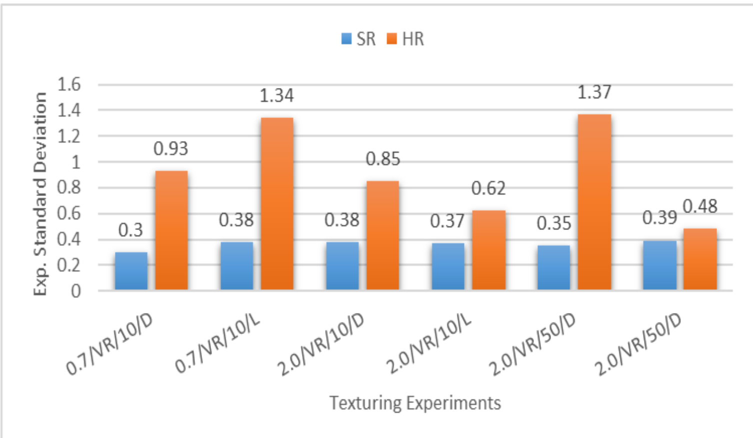


Figure 12. Experimental standard deviation (with very rough roll-VR)

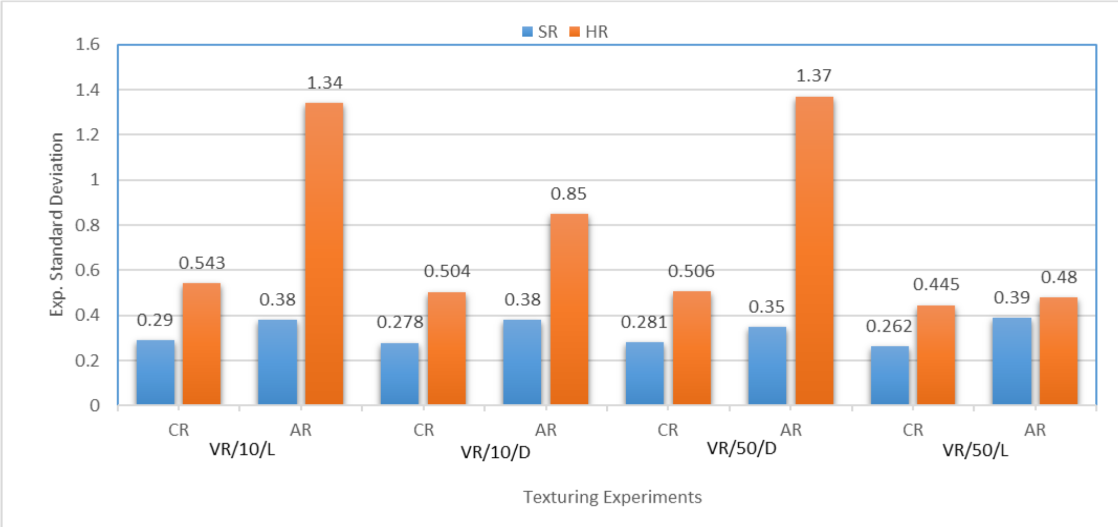
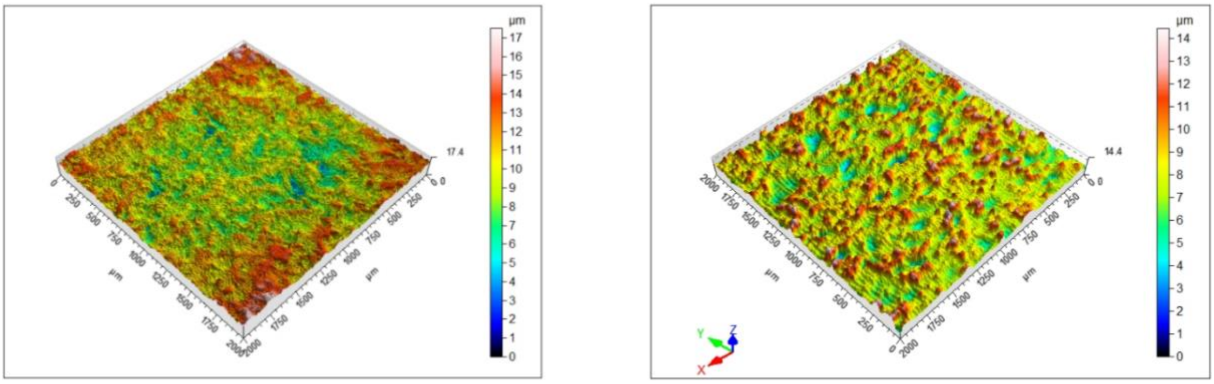


Figure 13. Comparison of standard deviation in CR and AR based on thickness reduction (CR data is taken from other article (Çolak & Kurgan, 2018))



(a) AR (standard deviation: 0.15) **(b)** CR (standard deviation: 0.08)

Figure 14. 3D optical field scan image for 2.0/R/10/SR/L conditions: **(a)** AR, and (**b)** CR

4.4.2 Lubrication effect

When we look at Figure 15 and Figure 16, it is seen that the roughness distribution changes depending on the surface condition (dry or lubricated) in AR. A lower standard deviation is obtained in dry rolling at lower speeds, while a lower standard deviation is obtained in lubricated rolling at higher speeds. However, in the previous study (Çolak & Kurgan, 2018), the standard deviation was lower at each speed value (lower or higher) in lubricated rolling. This can be attributed to the fact that while the hydrodynamic effect occurs at higher speeds in AR, this effect cannot be shown at lower speeds despite the lubricant. 3D surface scans were used to visualize this phenomenon. Figure 17 shows 3D surface topography images for the tests under 2.0/R/50/SR conditions. Comparing Figure 17a for dry AR with Figure 17b for lubricated AR, it is seen that the surface of lubricated rolled has a more homogeneous surface roughness at a higher speed (50 rpm). The roughness values measured manually on the material surface also parallel this result. In lubricated rolling, the standard deviation is 0.10, but in dry rolling, it is 0.15. It is seen that the surface of the symmetrical rolled sample has a more homogeneous roughness than the asymmetrical rolled surface under lubricated conditions when comparing Figure 17b with Figure 17c, showing the conventional rolled surface topography.

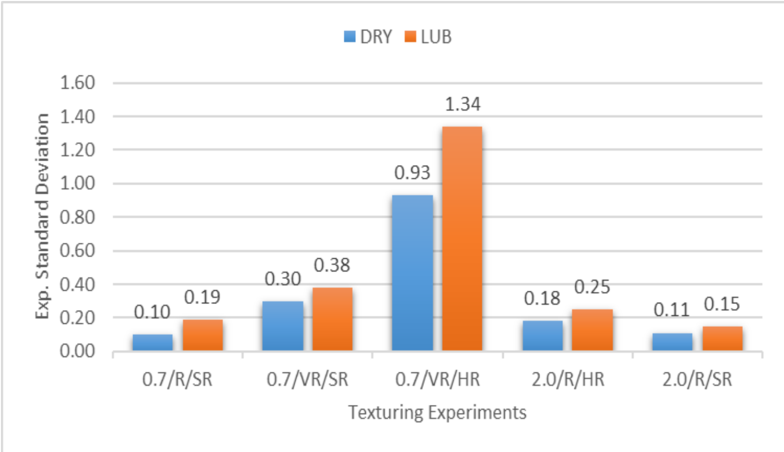


Figure 15. The effect of lubrication on standard deviation at low speed (10 rpm)

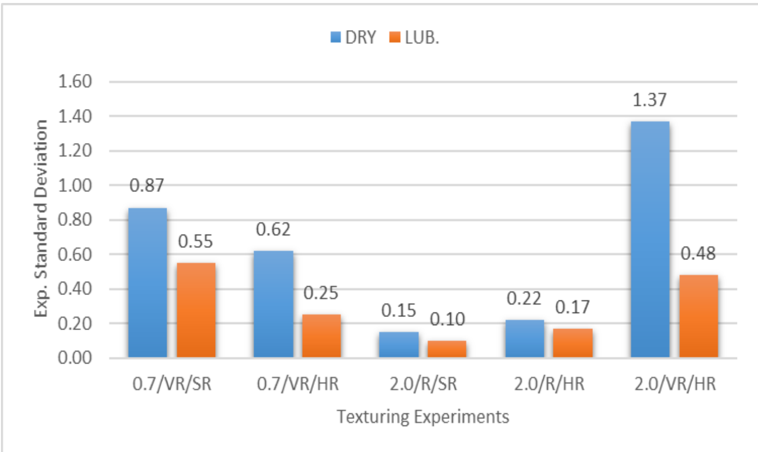
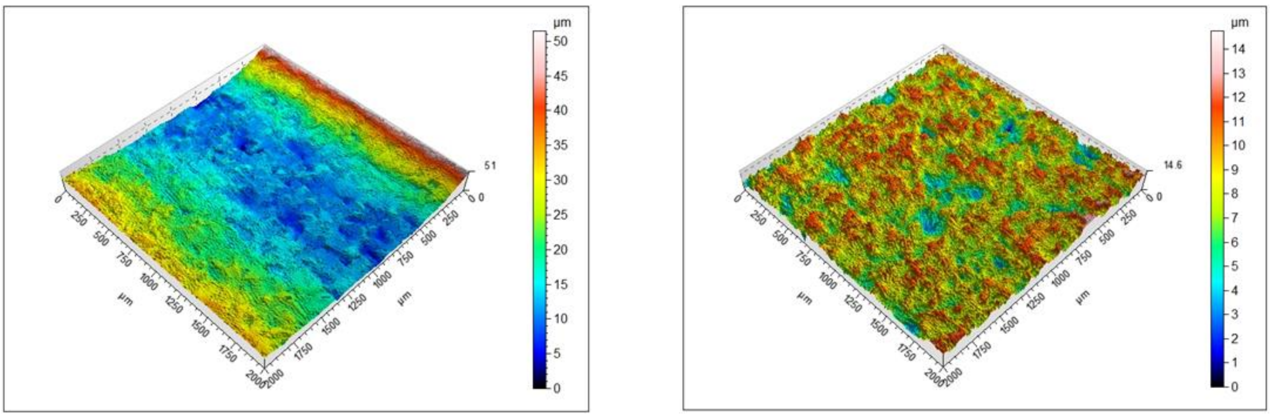
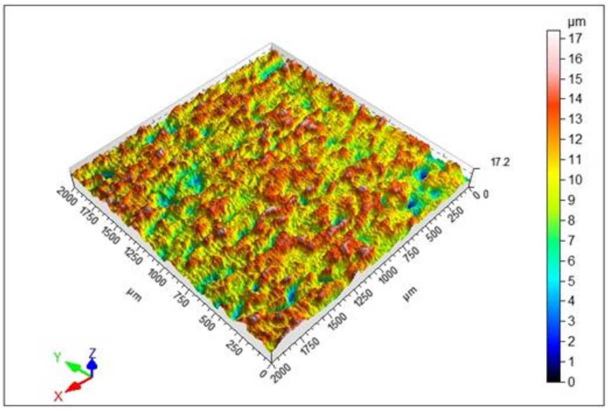


Figure 16. The effect of lubrication on standard deviation at high speed (50rpm)



(a) Dry AR (standard deviation: 0.15)

(b) Lubricated AR (standard deviation: 0.10)

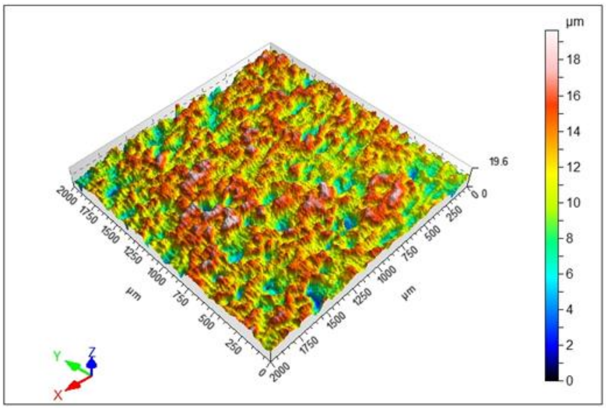


(c) Lubricated CR (standard deviation: 0.09)

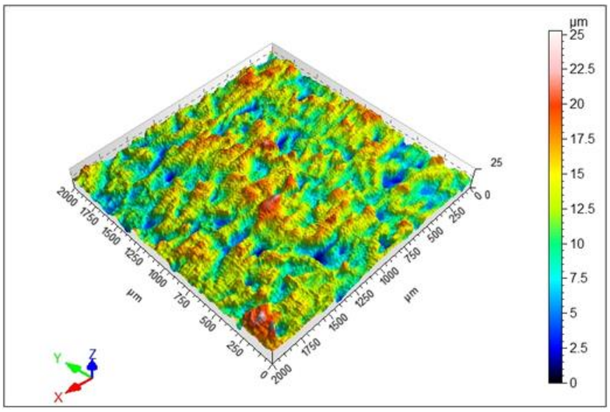
Figure 17. Rolling under 2.0/R/**50**/SR conditions: **(a)** Dry AR, (**b)** Oily AR, and **(c)** Oily CR

4.4.3 Speed effect

In most of the AR tests performed at different speeds, it was observed that the roughness distribution changed depending on the rolling speed. Considering the test result conducted under 0.7/R/HR/D conditions, it is seen that the roughness distribution increases with the speed increase in AR (Fig. 18). The roughness values measured manually on the material surface are also parallel to this result. The standard deviation is 0.17 at lower speeds and 0.22 at higher speeds. This was also the case in CR (Çolak & Kurgan, 2018).



(a) 10rpm (standard deviation: 0.17)



(b) 50rpm (standard deviation: 0.22)

Figure 18. 3D optical field scan images for 0.7/R/HR/D conditions at various speeds: **(a)** 10rpm, and **(b)** 50rpm

When the tests' results were compared with those obtained in the other study (Çolak & Kurgan, 2018), it was found that the standard deviation was more significant in AR under the same conditions. This is assumed to be because asymmetrical circumstances provide a higher sliding distance on the material surface (Fig. 1). Although fast asymmetrical rolling is an advantage in terms of both the production tonnage and the low tendency of the material to bend, it is seen that there is no advantage in terms of roughness homogeneity on the material surface. This shows that asymmetrical rolling is unsuitable for producing materials that should have homogeneous surface roughness.

5. Discussion

As in CR, roughness transfer increases with increasing rolling force in AR. In the same conditions, the higher rolling force in thicker material than thinner material means that the AR method is more effective in roughening thicker material. Conversely, in CR, the rolling force is higher in thinner materials. While the roll roughness does not have much effect on the rolling force in the use of thicker material, it is higher in the very rough roll comparing the rough roll when using thinner material.

Contrary to CR, transfer decreases as speed increases in AR. On the other hand, due to the rolling force, which causes the transfer to increase, decreases as the speed increases; there are two opposite effects on the transfer change.

The fact that the transfer is higher in dry rolling, and the standard deviation is lower at lower speeds and in the dry condition results in the conclusion that dry AR at lower speeds is more appropriate for suitable surface topography. If asymmetric rolling is to be conducted at higher speeds, a lubricant should be used to obtain a more homogeneous surface. However, the standard deviation in lubricated AR is more significant than in lubricated CR. The standard deviation is lower for rough and very rough rolls at a minor thickness reduction but not as low as in CR.

One advantage of AR is its lower rolling force (This advantage is only seen in thinner material in this study.) and lower torque comparing the CR process (Vincze et al., 2020). However, the fact that the increase in the rolling force at high speeds is higher than the increase in CR shows that AR is not suitable for rapid and mass production. The decrease in roughness transfer and increase in roughness distribution range as the speed increases is another difficulty to rapid and mass production with the AR method. AR can be applied after CR to increase material strength rather than to obtain good surface conditions (Cho et al., 2013; Muñoz et al., 2021). Another advantage of the AR method is that it can reduce the thickness more than CR with the same roll gap (Vincze et al., 2020).

Although the curvature of the sheet due to asymmetry is an obstacle to working in tandem order, it can be seen as an advantage in facilitating the down-coiling process. Applying multiple passes and turning the material with each pass can reduce the curvature effect in the machined sheet. It can also be reduced by adjusting the thickness reduction and by equipping the rolling mill with a table roller (Fajfar et al., 2017; Kiefer & Kugi, 2008).

Changes in dislocation densities and grain size are more pronounced on the surface of the material processed by AR than in CR conditions. This is an advantage in producing materials where the hard core of the surface is desired to be ductile. If conducted under the same conditions as CR, AR stands out mainly because it provides higher strength on the material's surface and requires lower rolling forces.

6. Conclusion

This work experimentally investigated the influences of rolling variables on roughening characterization in AR, and the findings are below.

- Lubricated rolling tests revealed that lubrication reduces roughness transmission by 13-45 per cent. However, this rate is around 7–23% in conventional rolling. Also, lubricated rolling provided a more homogeneous roughness distribution at higher speeds (around 22-65%), while dry rolling provided this at lower speeds (around 26-90 %). Lubricated symmetrical rolling has a homogeneity advantage at all speeds, and this rate is 16–35% at lower speeds and 5-27% at higher speeds.
- As the thickness reduction increases, the rolling force increases, as in CR.
- As the speed increases, although the rolling force, which acts to increase the roughness transfer, increases (max. 7%), the introduction of roughness decreases (max. 45%) but the roughness distribution range increases at around 30%. However, with the increase in speed in symmetrical rolling, a maximum of 12% in rolling force, there was an increase of up to 57% in transfers.
- The rolling force is higher (around 11–72%) when using a thicker material than thinner material. However, the rolling force in symmetric rolling is 24–38% higher in thin material.
- While the roll roughness does not have much effect on the rolling force in using thicker material, it is higher (around 22-88%) in the very rough roll compared to the rough roll when using thinner material. However, as the roll roughness increased in symmetrical rolling, there was an increase in the rolling force of 6-44%, independent of the material thickness.
- The standard deviation was lower in lower reduction ratios using rough (around 19-56%) and very rough rolls (around 19-72%). Conventional rolling (CR) ratios are 20-45% and 40-55%, respectively.

This study aims to provide information for parameter selection to generate a good surface roughness on sheet metal in AR. However, the test results revealed that AR is unsuitable for getting a surface roughened sheet compared to the CR.

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Authors' Contributions

All authors contributed equally to the study.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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