EXPERIMENTAL INVESTIGATION OF ROLLING PARAMETERSAFFECTING ROUGHNESS TRANSFER IN ASYMMETRICAL ROLLING

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Zahoor AHMED

ABSTRACT

M. Sc. Thesis

EXPERIMENTAL INVESTIGATION OF ROLLING PARAMETERS AFFECTINGROUGHNESS TRANSFER IN ASYMMETRICAL ROLLING

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Institute of Graduate Programs
The Department of Mechanical Engineering

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The sheet metals must have a particular level of roughness on their surface to obtain high-quality forming and dyeing solutions. This roughness is introduced during the rolling process with roughened rolls, a technique known as temper rolling. The rolling parameters determine the roughness level of the roll transferred to the material. This study investigated the effects of rolling parameters on roughness transfer. The experiments were carried out on a laboratory scale using a 2-high rolling mill mechanism fitted with load-cell monitoring the rolling force using ERD6112 grade samples with a 0.7 mm and 2 mm thickness. While the roll speed ranged from 10 to 50 rpm, only two different reductions (100µm, 200µm) were given to the samples. The top roll was roughened to meet the asymmetrical conditions, while the bottom one was chosen to be bright and large. Surface roughness measurements were taken from the rolled samples using a stylus profilometer, and the roughness values were calculated as the mean and standard deviation, and 3D scanning images were obtained.The results of the experiments were analyzed based on factors such as rolling parameters, roughness introduction, and standard deviation.

According to the results obtained, a higher rolling force is obtained, which increases the roughness transfer as the rolling speed increases. The influence of rolling speed on standard deviation varies linearly. Also, samples rolled in the presence of a lubricant showed reduced roughness transfer. Lubricated rolling produced a more homogenous roughness distribution than dry rolling at higher speeds, but dry rolling made it at lower rates. It was discovered that thicker materials have a more significant rolling force. Roll roughness does not significantly affect the rolling load when the sample is thicker, but this impact is more noticeable when using thinner material and a very rough roll.

The surface roughness of the sheet is imparted by conventional rolling (CR) with textured rolls. Although many studies have been published regarding CR and AR, more research on roughness transfer in AR needs to be done. This research aims to provide information for parameter selection to create good surface roughness on sheet metal in AR. Yet the test results revealed that AR is not a suitable method to get a surface roughened sheet compared to CR.

Keywords : Asymmetrical rolling, Surface roughness, Roughness transfer, Homogeneous roughness, Roughness retention

Science Code : 91438

ÖZET

Yüksek Lisans Tezi

ASİMETRİK HADDELEMEDE PÜRÜZLÜK TRANSFERİNİ ETKİLEYEN HADDELEME PARAMETRELERİNİN DENEYSEL OLARAK İNCELENMESİ

Zahor AHMED

Karabük Üniversitesi
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Şekillendirme ve boyamada kaliteyi tutturmak için sac yüzeyinde belirli bir seviyede pürüzlülük olmalıdır. Bu pürüzlülük, temper haddeleme olarak bilinen bir teknik olan pürüzlendirilmiş merdanelerle yapılan haddeleme işlemi sırasında ortaya çıkar. Malzemeye aktarılan merdane pürüzlülük seviyesini haddeleme parametreleri belirler. Bu çalışmada, haddeleme parametrelerinin pürüzlülük transferi üzerindeki etkileri incelenmiştir. Deneyler, 0,7 mm ve 2 mmkalınlığındaki ERD6112 kalite malzeme kullanılarak, haddeleme kuvvetini görüntüleyen yük hücreli, laboratuvar ölçeğinde 2'li hadde düzeni kullanılarak gerçekleştirilmiştir. Merdane hızı 10ila 50 rpm arasında değişirken, numunelere sadece iki farklı ezme (100µm, 200µm) verilmiştir. Asimetrik haddeleme koşullarını sağlamak için üst merdane pürüzlendirilirken alt merdane parlak ve büyük çapta seçilmiştir. Haddelenmiş numunelerden stylus profilometre kullanılarak yüzey pürüzlülük ölçümleri alınmış ve pürüzlülük değerleri ortalama ve standart sapma olarak hesaplanmış ve 3 boyutlu tarama görüntüleri elde edilmiştir. Deneylerin sonuçları, haddeleme parametreleri, pürüzlendirme ve standart sapma gibi faktörlere dayalı olarak analiz edilmiştir.

Elde edilen sonuçlara göre, haddeleme hızı arttıkça pürüzlülük transferini artıran haddeleme kuvveti daha yüksek elde edilmiştir. Haddeleme hızının standart sapma üzerindeki etkisi doğrusal olarak değişmektedir. Ayrıca, bir yağlı haddelemede numuneler, düşük pürüzlülük transferigöstermiştir. Yağlı haddeleme, yüksek hızlarda kuru haddelemeye göre daha homojen bir sağlarken, kuru haddelemede pürüzlülük dağılımı düşük hızlarda elde edilmiştir. Haddeleme kuvvetinin kalın malzemelerde daha yüksek olduğu görülmüştür. Numune kalın olduğunda haddeleme yükü merdane pürüzlülüğünden önemli ölçüde etkilenmezken, bu etki daha ince malzeme ve çok pürüzlü merdane kullanıldığında daha belirgindir.

Sacın yüzey pürüzlülüğü, pürüzlendirilmiş merdanelerle geleneksel soğuk haddeleme ile sağlanabilmektedir. Geleneksel haddeleme ve asimetrik haddeleme ile ilgili birçok çalışma yayınlanmış olmasına rağmen asimetrik haddelemede pürüzlülük transferi ile ilgili araştırma yok denecek kadar azdır. Bu çalışma, asimetrik haddelemede sac yüzerinde iyi bir yüzey pürüzlülüğü oluşturmak için parametrelerin belirlenmesine yönelik bilgi sağlamayı amaçlamaktaydı. Ancak test sonuçları, asimetrik haddelemenin geleneksel soğuk simetrik haddelemeye kıyasla yüzeyi pürüzlendirilmiş sac elde etmek için uygun bir yöntem olmadığı sonucunu ortaya koymuştur.

Anahtar Kelimeler : Asimetrik haddeleme, yüzey pürüzlülüğü, pürüzlülük transferi, homojen pürüzlülük, pürüzlülük istikrarı.

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SYMBOLS AND ABBREVIATIONS

SYMBOLS

Ra : Average Arithmetic Roughness
Pc : Peaks Per Centimeter
RPc : Number of Peaks
R : Roll Diameter
F : Rolling Force
Vo : Material Input Speed
Vf : Material Output Speed
Vr : Roller Circumfixal Speed
L : Contact Arc Length
ho : Input Thickness.
hf : Output Thickness.
μ : Friction Coefficient
wo : Initial Material Width
wf : Final Material Width
σ avg : Mean yield strength of the material
σmean : Mean Stress
e1 : Material Input Thickness
e2 : Material Output Thickness
σ : Stress
P : Rolling Pressure
N : Neutral Point.
n : The number of stands
vn-1 : The speed of the strip at the entry
en-1 : The entering value of materials thickness
vn : The speed of the strip at the exit
en : The exit value of materials thickness

Ra0 : The initial surface roughness
Ra1 : The surface roughness of rolled materials
Rar : The roll surface roughness.

ABBREVIATION

AR : Asymmetrical Rolling
CR : Conventional Rolling
SR : Smaller Reduction
HR : Higher Reduction
VR : Very Rough
TRM : Tandem Rolling Mill
FEM : Finite Element Method
KBÜ : Karabük Üniversitesi
HSM : Hot Strip Mill
RTR : Roughness Transfer Ratio
RPM : Revolutions Per Minutes

PART 1

INTRODUCTION

Flat steel production: It can start by melting scrap iron in electric arc furnaces with the help of electrical energy or by producing liquid raw iron in integrated iron-steel facilities. The liquid raw iron from smelting the ore with coke in blast furnaces is purified from slag and taken into torpedoes. The liquid raw iron in the torpedoes is desulfurized in the desulfurization plants and then transported to the steel mill. In the steel shop, by adding scrap and various alloying elements that differ according to the desired quality, the carbon ratio in the liquid raw iron is reduced by the pure oxygen blowing method. Thus, liquid raw iron is converted into liquid steel. The liquid steel produced is poured into the moulds continuously in the continuous casting facilities, solidified in the desired dimensions and turned into a semi-finished product in the form of slabs or billets. The steel cast in the form of slabs in continuous casting facilities is annealed in furnaces up to a temperature of approximately 1200 °C, then hot rolled, thinned to a thickness of 1 mm according to the facility's capacity, and rolled into coils. The scale formed on the material surface during hot rolling must be cleaned from the material before cold rolling. After the coil is opened and cleaned by being treated with sulfuric acid or hydrochloric acid in the continuous pickling line (CPL), the material is thinned by 25-80% by cold rolling, and the cold product is turned into galvanized, or tin-chrome coated packaging steel.

The grain of the cold rolled material elongates, undergoes strain hardening and loses its formability. This material has a full hard structure and can only be used where ductility and flatness are not required. In this state, the material must be subjected to a heat treatment. Recrystallization is ensured by annealing at a temperature of approximately 600 °C in the continuous annealing line. Due to cold rolling, the grain structure becomes anisotropic and turns into an isotropic structure by annealing. After annealing, the material is immersed in hot zinc baths and subjected to galvanization

(Hot Dip Galvanizing Process). Depending on the usage area, the material can also be used as it is without being coated.

In places where the surface appearance is of primary importance and planarity, surface roughness, and surface quality are essential, the material should be passed through the skin-pass rolling. Temper rolling is an ironing mill where approximately 1% elongation is given. Suppose the material thickness reduced by exceeding the yield stress in this rolling mill, where there is no thinning, is given the final form without waiting for deformation ageing after temper rolling. In that case, a better surface quality will be obtained since no significant yielding will be observed. Coil breaks, wavy appearance on the material surface and traces of lüders bands are eliminated by this rolling. After this rolling, the material is lubricated, wrapped as a coil, packaged, and shipped to the customer. Temper rolling is done with roughened rollers in cases where the material surface is desired to be rough.

Asymmetrical rolling (AR) is a recent technique that produces a speed disparity between the rolled material's top and bottom surfaces, stimulating shear deformation over the whole thickness and enhancing the quality of the metals. The very efficient method of AR makes it possible to develop heterogeneous microstructures within the material, leading to a well-balanced set of mechanical characteristics, most notably through forming plastic gradients. Due to the asymmetry and this heterogeneous structure, there is no deterioration in the strip profile but an improvement.

This study investigated how the roughness transfers from the roughened roll to the material during asymmetric rolling. There are many factors affecting this transfer. Among these factors, the effect of lubrication status, reduction ratio, roll roughness value, rolling speed and rolling force on roughness transfer was investigated experimentally. The surface roughness of the sheet is imparted by conventional rolling (CR) with textured rolls. Although many studies have been published regarding CR and AR, more research on roughness transfer in AR needs to be done. This research aims to provide information for parameter selection to create good surface roughness on sheet metal in AR. Yet the test results revealed that AR is not a suitable method to get a surface roughened sheet compared to CR.

PART 2

LITERATURE REVIEW

Roughness transfer has become an essential research topic in the flat steel industry. This literaturereview summarizes the findings of previous studies investigating the factors affecting roughness transfer in this process. This study aims to present the results of an experimental investigation intothe rolling parameters that affect roughness transfer in asymmetrical rolling.

Huang [1] used one-pass asymmetric rolling on magnesium alloys. However, smaller craters generated in the textured region during manufacturing are suitable for lubricating oil. The textured surface offers consistent reflectivity after painting if it is formed randomly. As a result, dense and deeper craters on the textured surface improve the coating of the alloy and its aesthetic properties. Experiments on multi-pass asymmetric rolling by Kim also revealed that the texture in the middle thickness section of the sheet stays almost identical to that of symmetric rolling [2]. Despite the considerable reduction in passes (up to 63 percent), they detected negligible texture rotation because their original texture was a firm basic texture. Such a texture is highly stable under simple shear [3].

The transfer of roughness from the roll to the material surface during rolling is influenced by several factors. The initial investigation into asymmetric rolling was undertaken by Sachs and Klinger in 1948, establishing a foundational study on the topic and developing a homogeneous deformation model [4]. The tribology of any metal sheet plays a vital role in metal properties, such as reliability and viability, even in micro-scale forms. However, shrinking from the macro to the micro-scale substantially increases friction. The friction behaviour at the in-contact and the transmission of surface roughness during the rolling process are influenced by imprecision flatness in surface roughness [5]. Yeong-Maw Hwang performed a numerical and simulation study on asymmetrical sheet rolling. It revealed that the relative bond length increased as the reduction and friction factor increased [6]. According to the research of H. Xie, during asymmetric rolling with a similar diameter and differing rotational speed, the strip bends to the lower-speed roll, and when the value of the speed asymmetry parameter is increased as the length of the cross-shear zone in the roll bite rises with the strip curvature rises, but the force characteristics reduce. However, the neural points change dramatically [7]. According to G. Vincze, the roll diameters ratio is 1.5 provides a homogeneous shear deformation across the thickness and reduced rolling force and torque but also allows the production of thinner material with the same roll gap as in conventional rolling [8]. The average arithmetic roughness (Ra) and peak count in peaks per centimetre (Pc) are two well-known parameters for defining a surface.

Numerous experiments have been conducted on reduction ratios. The first experiment conducted by Ma et al. [9] revealed that materials rolled at lower reduction ratios and slower speeds exhibited lower surface roughness. Compared, those rolled at higher reduction ratios and faster speeds showed higher surface roughness. Additionally, the AFM images indicated that the increase in roughness was more pronounced under lubricated rolling conditions. Compared to the second experiment conducted by Bilal [10], increasing the reduction ratio and the rolling speed increased both the surface roughness of the roll and the roughness distribution range. Wauthier et al. showed a range of thickness reductions (32.2–36.8%) in tests that used different asymmetry ratios (1.10– 1.45), even though the spacing between the rolls and the roll surface roughness is the same [11]. Dong et al. discovered that when the reduction ratio grew, the strip surface topography resembled the roll surface topography [12]. Due to elastic deformation, it was impossible to achieve complete (100 per cent) roughness transfer, and there was no roughness transfer at extremely low reduction ratios, according to the findings of Wu et al. They noticed that the rolling force and roughness transfer increased when the reduction ratio increased [13].

Looking back, we can see that roughness transfer is a relatively modern technology for usually improving material characteristics. Lenard investigated the effect of work roll roughness on various rolling process parameters, determining that whenever the roll roughness reaches a specificlevel. In addition, he found that the transfer roughness increased with the rolling force [14]. According to Kijima [15] and Shi [16] research, when the diameter of the roll reduces, the peak pressure increases dramatically, as does the transfer of roughness. Rui et al. [17] found that whenthe roughness of the first stand roll was large and the next was lower, a smaller roughness range was produced on the metal surface. Because of FEM simulations done with two different temper mills and individually modifying average arithmetic roughness (Ra) and a high number of peaks (RPc) with the use of the PDT (Pomini digital texturing) technique can result in a homogeneous surface [18]. According to Kimura, roughness transfer increased as elongation increased [19]. TheSMS Group and Kimura obtained similar findings, and this increase in roughness transfer was noticeable in thinner materials [20]. Kijima performed conventional rolling experiments to examine the correlation between rolling force and roughness transfer. By employing rolls with different radii and surface roughness, he found that the roughness transfer increased with the increasing rolling force for both roughnesses [21]. The latest experimental investigation on roughness transfer via Bilal [22], the law states that when the reduction rate increases, the surfaceroughness and roughness distribution range rise. This study aims to present the results of an experimental investigation into the rolling parameters that affect roughness transfer in asymmetrical rolling. The research is separated into five portions: process method, texture evolution, microstructure evolution, mechanical properties, findings, and future perspectives on this technology. In addition, the results will be supported with 3D surface images taken from the rolled surfaces. As can be seen, the absence of many publications in the literature on roughness transfer in asymmetric rolling makes this study an original one.

PART 3

INTRODUCTION OF ROLLING

3.1. ROLLING OPERATION

One of the most essential industrial metal-forming processes is rolling. It is the process by which a metal workpiece is passed between two rolls. This process minimizes the cross-section of the workpiece by generating compressive force through a set of rolls. Also, the material is compressed, causing a reduction in thickness and an increase in length, and formed into the desired shape of the workpiece. The process can be performed at high or low temperatures, depending on the desired properties of the finished product and the characteristics of the metal being worked. The flat rolling process involves passing a metal workpiece, commonly called the "strip," through straight rolls rotating in the opposite direction at various speeds throughout the rolling process. As a result of the contact between the rolls and the metal surface, the metal is subjected to significant compressive stresses that modify the strip's physical and mechanical properties.

Rolling is the process of passing a metal workpiece between two rolls. Figure 3.1 shows a rolling mechanism with two rolls (2-hi) moving in opposite directions with material going between them. Because the roll gap area is set below the cross-sectional size of the input material, the input material is introduced into the gap between both rolls from one side. It exits the gap on the other end with a smaller cross-section. Until getting the required final form of rolled material, the material passes through the rotating rolls numerous times in opposite directions, called a reversible mill.

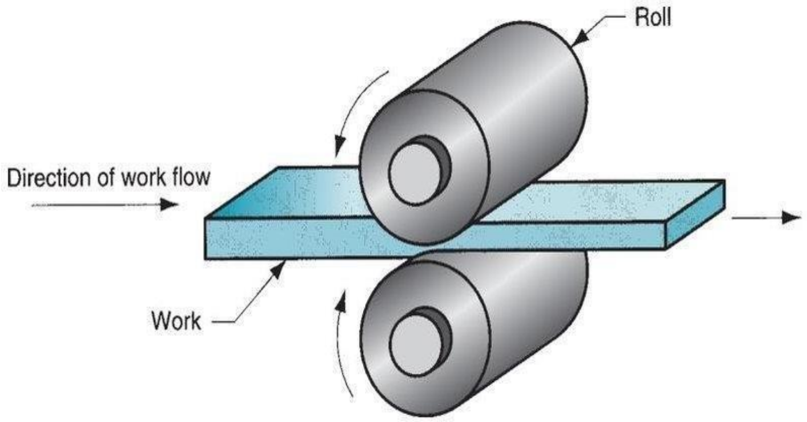


Figure 3.1. The principle of rolling operation.

Rolling is efficient and economical for large-scale, high-quality metal products with uniform dimensions and features. Rolling is carried out by gradually thinning the material in stands (fig.3.2) consisting of stacked rolls on each other. Continuous rolling systems such as tandems are used to speed up production. The tandem continuous mill (TCM) comprises numerous stands through which the material is continually passed, as shown in Figure 3.3. Sheet thickness is reduced to a certain extent at each stand. Between the first and last stands, the overall decrease can be substantial.

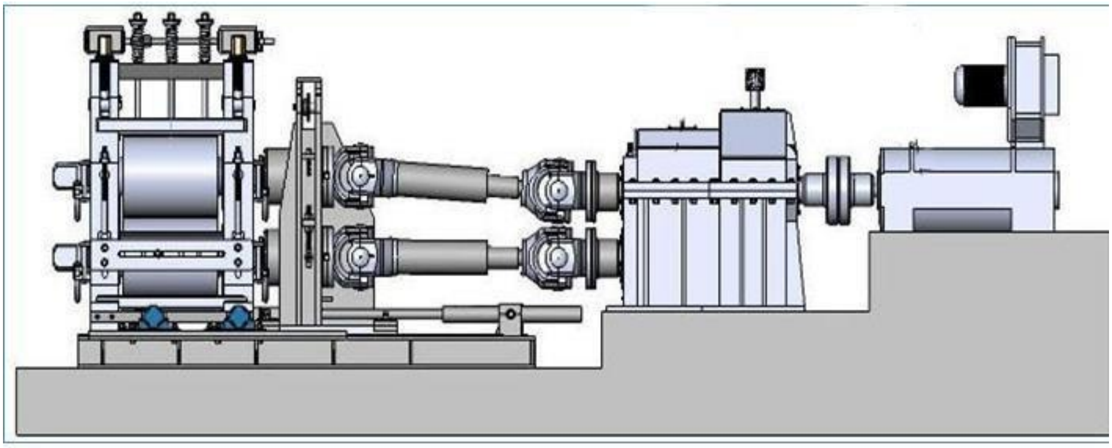


Figure 3.2. Schematic representation of the horizontal rolling mill stand.

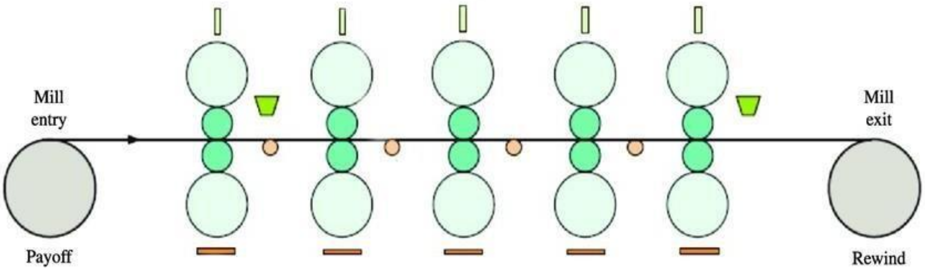


Figure 3.3. Tandem continuous mill (TCM).

The rolling process can significantly improve the mechanical properties of the metal, suchas its strength, hardness, and ductility. This is due to the deformation of the metalworkpiece during the rolling process, which changes its microstructure and imparts desiredmechanical properties. These improved material properties can lead to a stronger, more durable, and more reliable finished product, leading to increased product performance andonger service life.

Rolling is the primary method used in manufacturing sectors to process ferrous and nonferrous metals and alloys into useful forms. Rolling is a highly efficient and productive method of metal forming. The rolling technique produces various products for several industries, including automotive, construction, aerospace, and electrical. There are several types of rolling, including hot rolling, cold rolling, continuous rolling (Fig. 3.4), and reversible rolling, each with unique advantages and disadvantages.

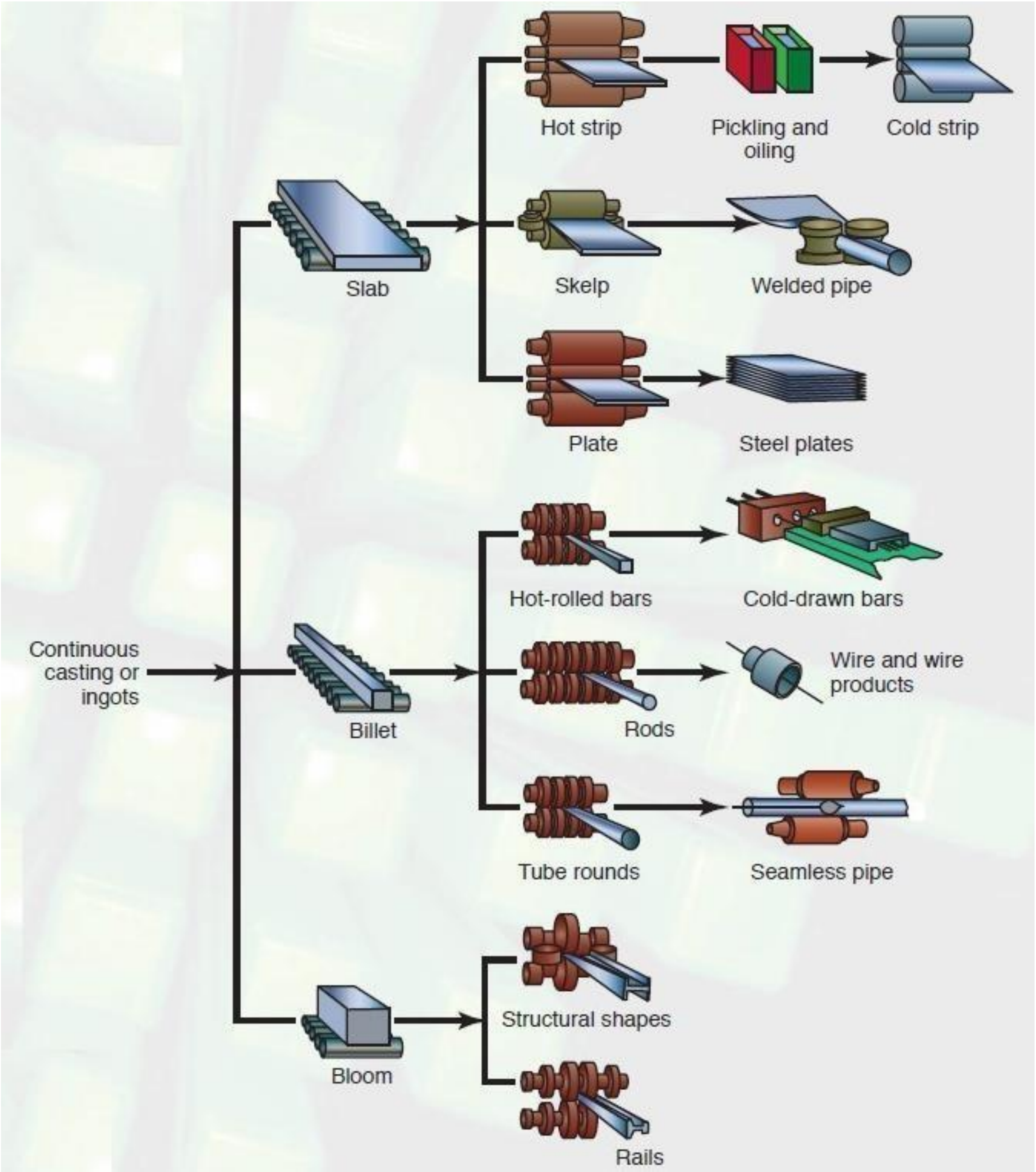


Figure 3.4. Schematic outline and products of various flat-rolling and shape-rolling operations.

3.1.1. Hot Rolling

In flat product production, the hot rolling mill is critical in transforming the material into a final product known as black sheet iron, commonly used in various applications such as construction, machinery manufacturing, and railway vehicle manufacturing. However, the raw material, typically a metal slab or billet, is heated to elevated temperatures in a furnace. The heated metal is then passed through a roughing mill. The roughing mill is typically reversible, allowing the material to pass several times in both directions between the rolls. After the roughing mill, the material 30mm thick comes to a finishing mill with multiple stands (Fig 3.5). Each stand consists of large rolls that apply high compressive forces to reduce the thickness of the material and increase its length.

Figure 3.5. Hot Strip Mill (HSM).

It is important to note that slabs obtained through continuous casting have a non-uniform dendritic grain structure, which can result in a brittle and porous material. The rolling process above the re-crystallization temperature allows the grains to extend, leading to a directional and more compact structure. This results in a finer grain and a more formable structure, better suited for the various manufacturing processes shown in Figure 3.6. Additional functions such as cold rolling, annealing, and coating can be employed according to customer demands to enhance the material's properties further. Flat rolling is a complex and multi-step operation requiring precision and expertise to ensure high-quality products.

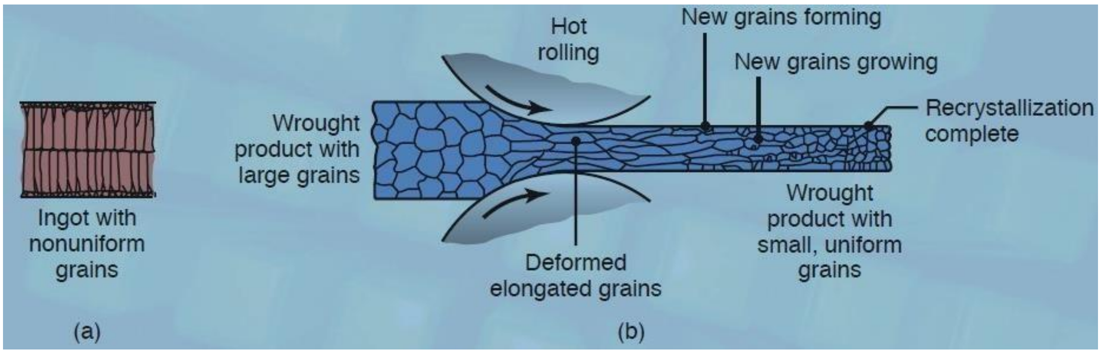


Figure 3.6. Changes in the grain structure of metal during hot rolling. a) ingot (non-uniform grain structure), b) refinement in the grain size during the process.

3.1.2. Cold Rolling

Cold rolling plays a crucial role in manufacturing by producing sheets, strips, and foil with better surface quality and high mechanical strength while keeping precise control over product parameters. It is commonly used for making sheets, plates, and metal strips for various applications, including automotive components, consumer electronics, construction materials, and food packaging.

The cold rolling method is done near room temperature, less than the material's recrystallisation temperature. It increases yield strength, tensile strength, and metal hardness, improving surface smoothness and straightness. The strip is passed between tough rolls during cold rolling, which involves high tension and roll forces. This is accomplished by making just one pass in tandem rolling mills (fig 3.3). A longitudinal section through a strip in the roll bite is shown in fig. 3.7 in each stand, the thickness is reduced from the entry value en-1 to n at the exit. Without any significant lateral spread, the thickness is reduced, and the length is increased. Thus, if vn-1 is the speed of the strip at the entry to stand n, and vn that at the exit, the conservation mass flow rate leads to the following relation:

$$Vn\bullet 1\cdot en\text{-}1 = vn\cdot en \qquad (3.1)$$

The strip thus accelerates as it moves through the mill.

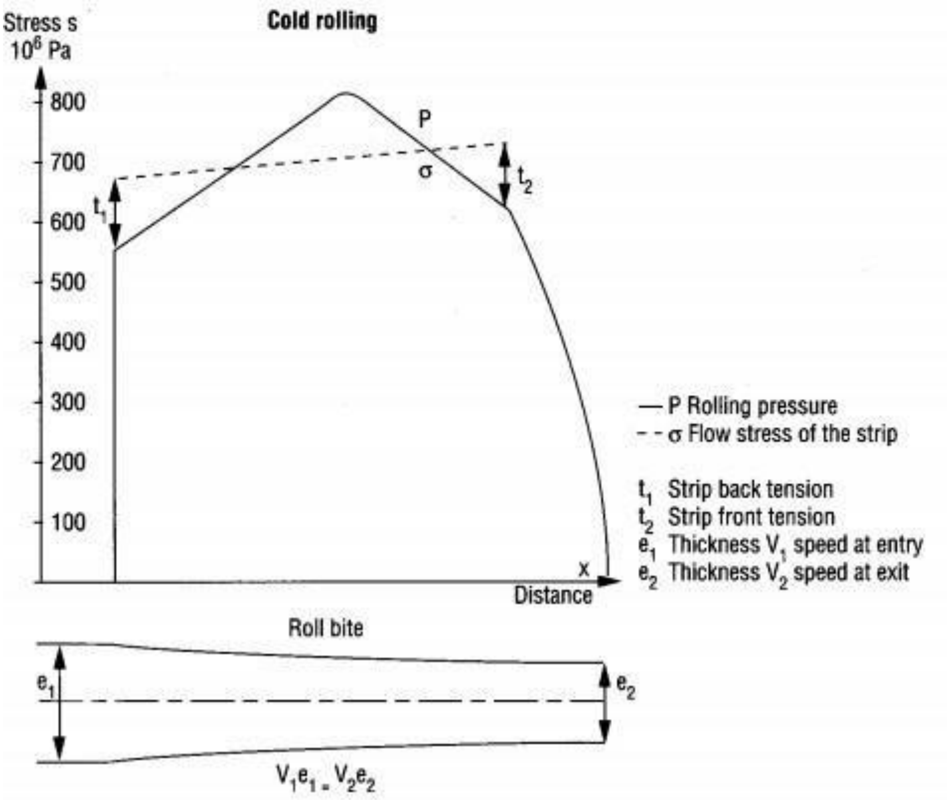


Figure.3.7. Variation of rolling pressure and strip flow stress (upper diagram) and strip thickness(lower chart) with a position in the roll bite of cold rolling mills.

3.1.3. Cooling and Lubrication

Even in cold rolling, a significant amount of heat from plastic deformation and friction needs to be addressed. Therefore, high coolant flow rates are required (several hundred m3/h per stand). The strip can also be cooled outside of the roll gap.

The rolling force increases as increase of friction coefficient between the material and therolls. So, it is essential to use lubrication properly to regulate and reduce the coefficient of friction. The material thickness is indicated by the letter "e" in Figure 3.8, and the amount of reduction in each curve is 0.1 mm. The rolling force increases dramatically in thin materials due to the friction coefficient. Therefore, lubrication should be done more effectively as the strip thins. Several types of oils are used, including animals' oils and synthetic petroleum oils.

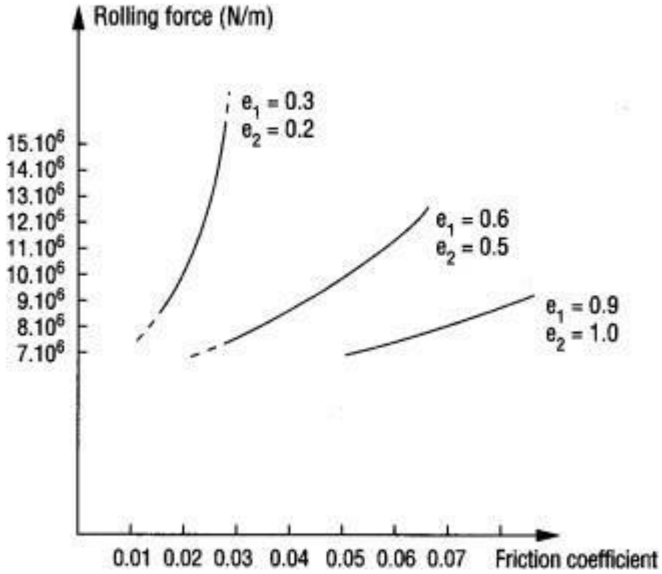


Figure 3.8. Friction coefficient-rolling force relationship.

The cold rolling method is a complicated process that involves the interaction of several factors. These are the factors.

- The rolling force varies with the material's yield strength and friction coefficient.Consequently, lubrication controls the flattening of the rolls.
- The excessive temperature in the contact area causes the oil film to break off and the formation of gauge traces due to micro-galling between the material and the rolls.
- Material surface roughness, which varies depending on work rolls and lubrication. Excessive lubrication (thick oil film formation, reduced contact areas between the material and roll, and oil-insulated (oil-free) rolls) leads to the formation of high roughness in the regions. In extreme cases, instability in the material flow leads to slipping and rapid wear of the rolls, which causes vibration in the rolling machine. This vibration leads to smoothness in the strip thickness in each cycle of the rolls.
- Warmed roll barrels swell and become dished, causing a transverse variation in strip thickness, and sufficient cooling is required to solve this problem.

3.2. MAIN PARAMETERS OF THE ROLLING PROCESS

3.2.1. Friction

A schematic representation of flat product rolling is given in Figure 3.9. In Figure 3.10, the material is hf thick when it passes through rolls with a distance less than this thickness between them. Meanwhile, the rolls rotate at a constant peripheral speed while the input speed of the material (V0) increases. Because although the amount of material (flow) passed in unit time is constant, the section narrows. The speed of the material as it passes through the rollers is equal to the linear speed of the rolls. This point is called a neutral point (no-slip point) in Figure 3.9. Up to this point, the material speed is lower than the roll speed; after this point, it is higher. Therefore, friction occurs between the roll and the material along the L contact arc, except for the neutral point. The friction force is in the direction of pulling the material before the neutral point, then in the opposite direction. For the rolls to pull the material in and for rolling to take place, it must be in the exit direction of the compound of these opposite-direction friction forces. Even if rolling is cold due to this friction and plastic deformation, the material temperature can rise by 50–65 °C [27].

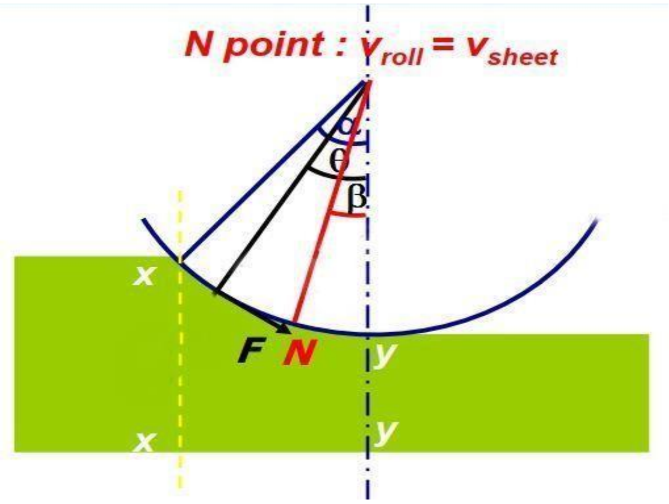


Figure 3.9. The neutral point in roll gap (point N).

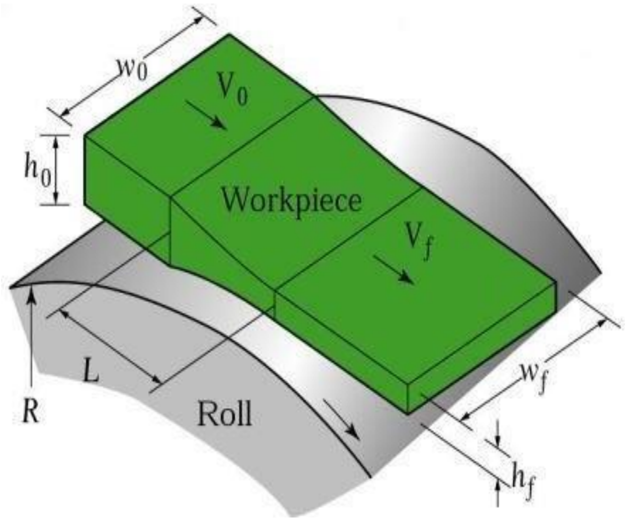


Figure 3.10. The basic idea of the flat-product rolling method (top roll not shown).

3.2.2. Rolling Force

A rolling force is exerted on a rolling body because of the interaction between the material surface and the rolls. Several factors influence it, such as thickness reduction, speed, material grade, roll radius, and surface roughness. In engineering, calculating rolling force is essential for understanding and optimizing the performance of various systems and machinery in material processing and manufacturing processes [27]. The rolling force (F) used to thin the material shown in Figure 3.11 acts in the opposite direction. This force can be calculated using Equation (1.2) for flat rolling.

$$F = L.\ w.\ \sigma_{avg} \tag{3.2}$$

Where w: material width, L: contact arc length, and σ_{avg}: mean yield strength of the rolledmaterial during deformation, as shown in Figure 3.10. The calculated force is less than the real force because friction is not considered in this calculation; this difference rises much higher in materials with high friction coefficients.

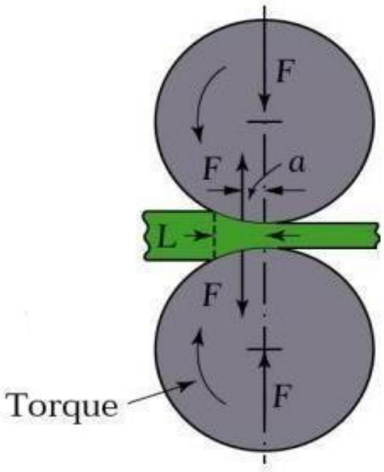


Figure 3.11. The rolling force (F) and torque of the rolls.

The contact area is flattened because the rolls bend due to rolling forces. This circumstance creates a challenge since the rolled material must have an accurate thickness. Rolls and bearings transmit considerable rolling loads to the housing (Fig. 3.12). Under this force, if the housing is not rigid enough, it can experience elastic form change, increasing the roll gap by up to 1mm. This is known as mill stretching and should be considered when determining the roll clearance based on the material thickness. In other words, the roll gap should be less than the desired product thickness.

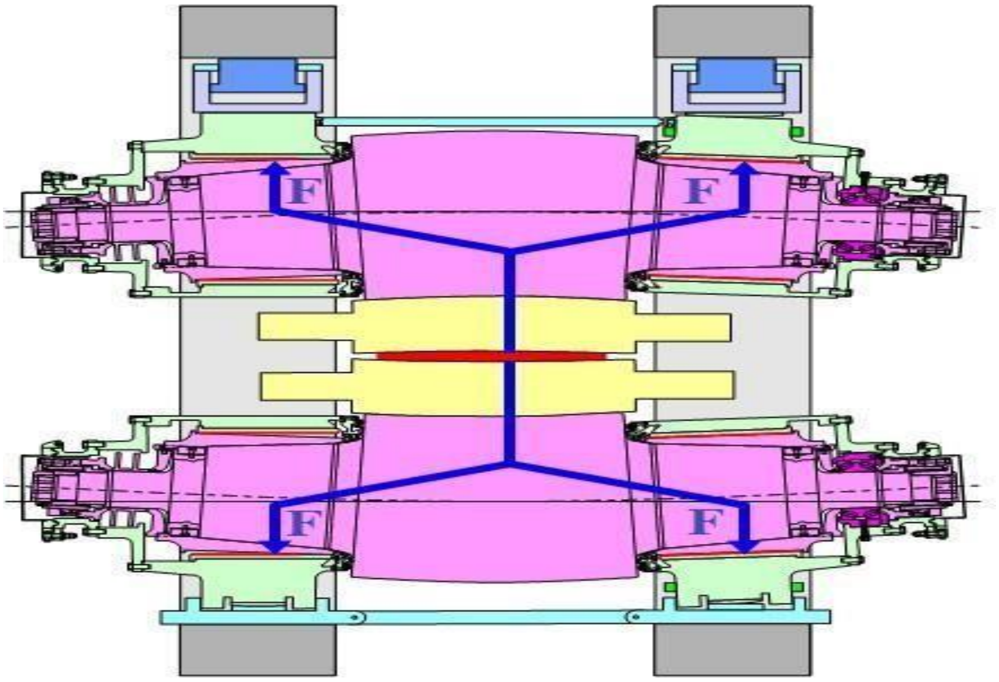


Figure 3.12. The distribution of rolling force in a 4-hi rolling stand.

Performing of rolling process under as low as possible rolling force is significant in terms of mill equipment (roll, bearing, etc.) and energy saving. The following should be considered to reduce the rolling force.

- Friction must be decreased.
- Smaller diameter rolls must be utilized (to minimize compressed material volume).
- Thickness reduction should be performed in smaller increments on every pass (toreduce the volume of formed material).
- Rolling should be done at an elevated temperature to lower the strength of thematerial.

3.3. ASYMMETRICAL ROLLING

Asymmetrical rolling (AR) is a recent technique that produces a speed disparity between the rolled material's top and bottom surfaces, stimulating shear deformation over the whole thickness and enhancing the quality of the metals. The very efficient method of AR makes it possible to develop heterogeneous microstructures withinthe material, leading to a well-balanced set of mechanical characteristics, most notably through forming plastic gradients [26]. Due to the asymmetry and this heterogeneous structure, there is no deterioration in the strip profile but an improvement [21]. However, In the conventional rolling (CR) process, which is a symmetrical rolling (Fig 3.13a), until the neutral point, the tangential friction force acts in the direction to draw the material into theroll. After the neutral point, the frictional force's direction is reversed and opposes the delivery of the sheet from the rolls [23]. Since the neutral points of both rolls are on the same vertical plane due to the symmetry shown in Fig 3.13a, 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 3.13c).

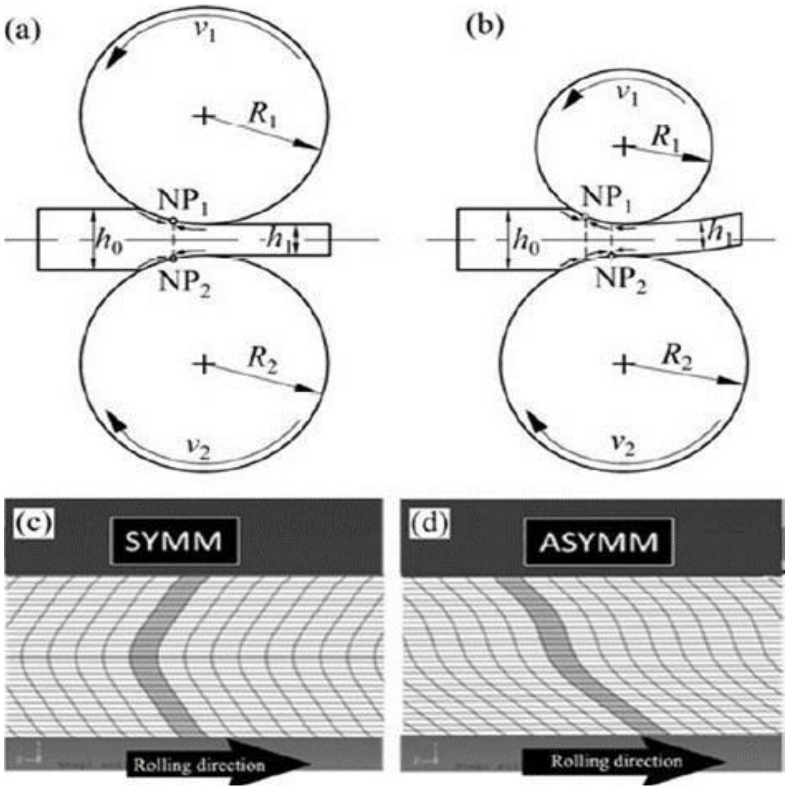
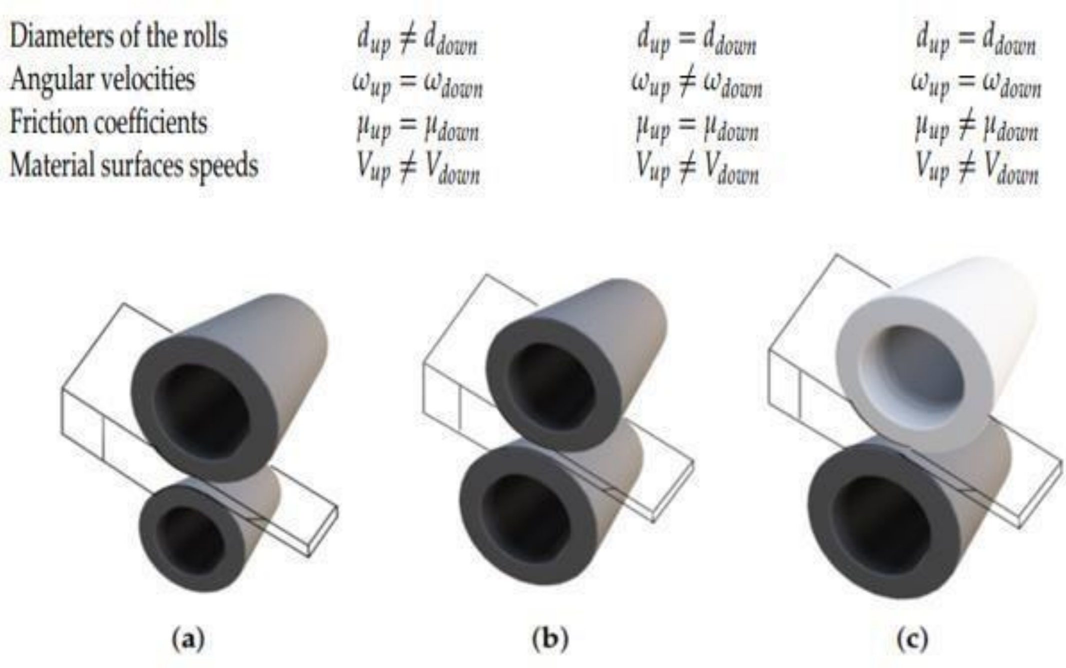


Figure 3.13. Schematic illustrations a) Symmetric rolling (R1=R2, V1=V2) b) Asymmetric rolling (R1<R2, V1<V2) c) Shear deformation texture through the thickness in CR d) Heterogeneous shear deformation texture through the thickness in AR [27].

There are three ways to achieve AR conditions: rolls with different radii, unequal rotation speeds, or different surface conditions. The methodology for the AR process is depicted in Figure 3.14, which also provides a visual representation of all three methods. 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 towards the entry side, while the neutral point of the larger roll (bottom roll) shifts towards the exit side due to the speed difference of both rolls (Fig 3.13b). 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 [26]. This shear strain changes the deformation stream and the evolution of the microstructure (Fig. 3.13d).



Diameters of the rolls	$d_{up} \neq d_{down}$	$d_{up} = d_{down}$	$d_{up} = d_{down}$
Angular velocities	$\omega_{up} = \omega_{down}$	$\omega_{up} \neq \omega_{down}$	$\omega_{up} = \omega_{down}$
Friction coefficients	$\mu_{up} = \mu_{down}$	$\mu_{up} = \mu_{down}$	$\mu_{up} \neq \mu_{down}$
Material surfaces speeds	$V_{up} \neq V_{down}$	$V_{up} \neq V_{down}$	$V_{up} \neq V_{down}$

Figure 3.14. The three methods approach for the asymmetric rolling process are illustratedas follows.: (a) The rolls have various diameters; (b) The rolls rotate at various speeds; c) The various roll surface conditions.

PART 4

EXPERIMENTAL WORK

4.1. TEST INSTRUMENTS AND MATERIAL

Rolling machines aim to press a metal sheet into a thinner sheet with the help of two rolls that compress the material as it enters the machine and rotates in opposite directions. Steel samples were tested on a two-high rolling system with a power output of 1.5 kW. Its two rolls can operate at speeds between 5 and 60 rpm (Fig. 4.1). To precisely analyze rolling forces, the digital measuring device was outfitted with a 100-tonne load cell. Three pieces of rolls, each with a distinct surface roughness, were used in the experiments. As seen in Fig.4.2, the top roll was roughened to achieve AR conditions, while the bottom roll is brighter and bigger. The specifications of the rolls are given in Table 4.1. The roll bearings are lubricated by an oil pump operated by a cam during the rotating movements. The system is equipped with a finger guard grid, as seen in orange, to minimize the possibility of work accidents during material charging.

Figure 4.1. The Rolling Setup.

Figure 4.2. The surface roughened roll.

Table 4.1. The specifications of the rolls used.

	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 diamond	Cold work tool steel (2379)
Very rough roll			8.0			
Bright roll	75	60	Less than 0.4	60	Ground	

4.2. SAMPLE PREPARATION

We provided the test material in ERD 6112 grade from Erdemir Steel Service Center as a sheet sample. Using a thickness of 0.73 mm and 2.0 mm, we cut the sample to the desired size and shape for testing purposes: 32 samples are 30 mm wide and 250 mm in long (Fig. 4.3a). It is crucial to ensure thesample is cut as accurately as possible to avoid errors in the test results. After that, the cleaning the sample to remove any dirt, oil, or other contaminants that may affect the test results. We use asolvent such as kerosene to clean the sample. The test parameters were inscribed on the sample via a permanent red pen (Figure 4.3 b). The material properties are given in Table 4.2, and chemical compositions are shown in Table 4.3.

Slitting of the samples. Test samples.

Figure 4.3. The preparation of the samples.

Table 4.2. The material properties

Standard	Grade	Erdemir Grade	Thickness (mm)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)	Surface Roughness (µm)*
DIN-EN 10130-2006	DC01	ERD6112	0.73	236.3	339.3	36	1.123
			2.00				

Table 4.3. The chemical composition of the material.

Material	%C	%Mn	%P	%S	%Si	%AI	%Ti
ERD6112	0,002	0,155	0,005	0,009	0,005	0,055	0,071

4.3. ADJUSTMENT OF THE THICKNESS REDUCTION

The T-shaped screw pulls the top roll up and down to change the distance between the rolls by manually twisting the T arm on the assembly shown in Figure 4.4 (a). The top and bottom roll move closer to one another by 0.7 mm with each rotation of the T adjustment arm. The top roll was reset using the T arm by contacting the inserted test sample and eliminating the cavity. The reset was conducted with a 100 kg preload (Figure 4.1 (a)). The precise dial gauge measures the top roll position, and the reset position is calculated (Fig. 4.4b). After removing the material by opening the rolls, the top roll was returned to the reset position read on the dial gauge with a preload of 100 kg. The dial gauge is used to calculate the thickness reduction from now on. The purpose of the reset is to guarantee complete surface contact by crushing components like burrs, which can increase the thickness measurement of the material. Put another way, the thickness reduction is based on the point reached with a preload of 100 kg. This reset procedure has been conducted for all tests in the same manner.

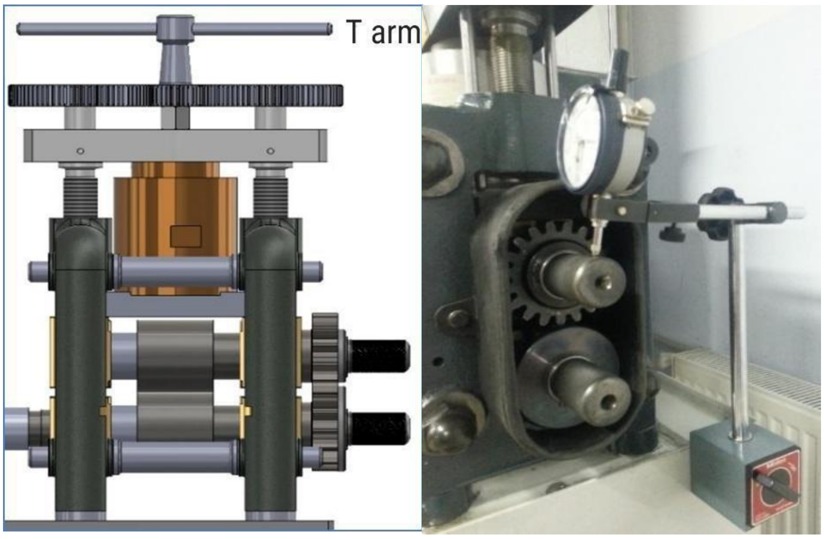


Figure 4.4. Adjustment of the thickness reduction a) The view of the T arm mechanism, b) Confirmation of thickness adjustment by dial-gaugec).

4.4. ROLLING EXPERIMENTS

The tests were conducted with the rolls in different roughness conditions, including different speeds and reduction ratios, at room temperature, in dry and lubricated conditions. These variables' indications are shown in Table 4.4. Two rolls were used during the test; the top roll was roughened to achieve AR conditions(as presented in Table 4.1), whereas the other had a bright surface and a bigger diameter.

Table 4.4. Rolling parameters.

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

4.5. MEASUREMENTS

4.5.1. The Measurement of Rolling Force

The load cell is a device that measures the rolling force in a rolling machine. It has a digitalscreen that shows the force as the rolling operation continues (Figure 4.5). The highest value on the load meter's screen was considered, even though the rolling force showed variations of up to 10% during the process.

Figure 4.5. Screen displaying the rolling force measured by the load cell.

4.5.2. Measurement of Material Thickness

Measuring the thickness of materials is an essential step in many laboratory procedures. They were measured by Mitutoyo micrometres in the metrology laboratory of the KBU Iron and Steel Institute, accredited by TURKAK, before and after the test (Fig.4.6).

Figure 4.6. The thickness measurement of the samples.

4.5.3. The Measurement of Surface Roughness

It's essential to clean off any oil and debris from the roll's or material's surface to ensure the accuracy and reliability of surface roughness measurements. Before measuring surface roughness, an effective cleaning procedure involves wiping the surface with kerosene. This process successfully removes any potential surface impurities that could impact the roughness values andenables recording accurate and reliable data.

To determine how much roughness is transferred from the rolls to the material after a test, we evaluated the roughness of the material's surface with the help of a Marsurf brand device, the m300 model. We achieved this by measuring the surface roughness from the beginning to the end of the surface material in all parts parallel to the rolling direction. We measured the roughened surface of the material six times for all the test samples, as seen in Figure 4.7.

Figure 4.7. The Surface Roughness measurements of the samples.

4.5.4. Roughness Transfer Ratio

The roughness transfer ratio indicates how much roughness is transferred from one surface to another after a rolling test. The roughness transfer ratio (RTR) from the roll to the material was calculated with Equation 1.3.

$$RTR[\%] = \frac{Ra_1 - Ra_0}{Ra_r - Ra_0} x100 \qquad (4.1)$$

In this equation, Ra_0 is the surface roughness of the material without rolling, Ra_1 is the surface roughness of the rolled material, and Ra_r is the roll surface roughness. We need to know the material's initial surface roughness (Ra_0) to measure how much roughness has been transferred during the rolling process.

PART 5

TEST RESULTS AND DISCUSSIONS

5.1. THE EFFECT OF ROLLING PARAMETERS ON ROUGHNESS TRANSFER

5.1.1. The Speed Effect

The roughening experiments were carried out with different speeds (10 and 50 rpm), while all other parameters remained constant. At lower rolling speeds, the roughness transfer is higher dueto the material experiencing more surface deformation and higher contact time between the rolls and the material during asymmetrical rolling (Figure 5.1). Qu et al. addressed the issue in their symmetrical rolling experiments by stating that the surface asperity flattens out when the speed rises, increasing the actual contact area. Additionally, they declared that quick rolling impacts this result because it accelerates the progressive shearing process in the contact zone [24]. Conversely,Ma et al. (2019) experimented with conventional rolling (CR) and found similar results. They stated that material roughness increased as the speed rose in their studies rates but at various speeds(5 rpm, 30 rpm, and 60 rpm), and they provided evidence for this with AFM pictures [12].

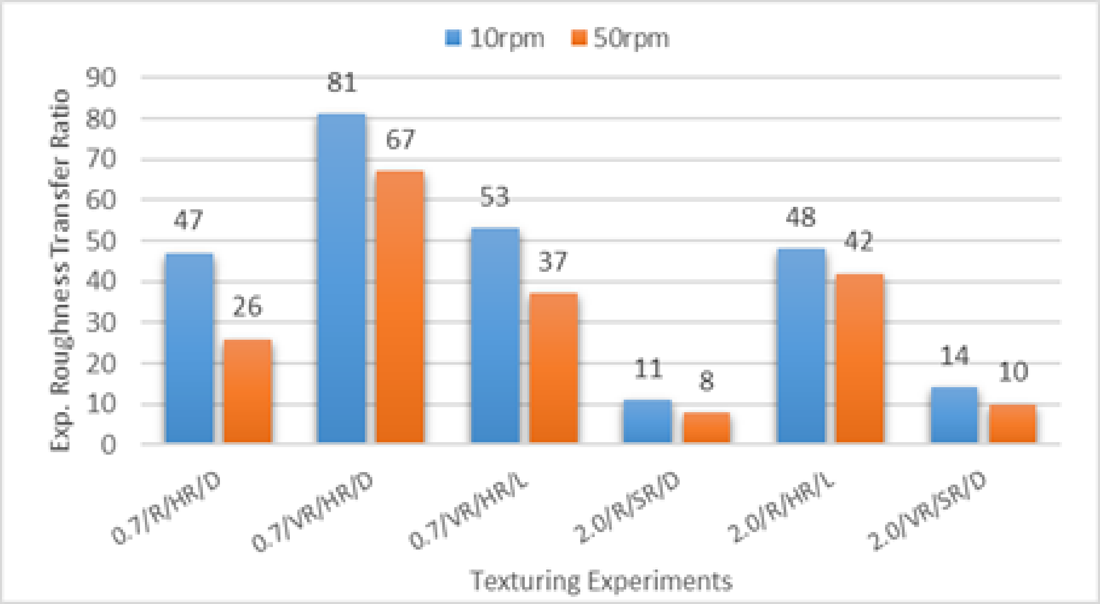


Figure 5.1. The speed effect on RTR.

5.1.2. The Lubrication Effect

The roughening tests were performed under various surface conditions, including dry and oily rolling, keeping other parameters constant. It was observed that the surface roughness of the material was found to be greater in dry rolling when compared to oily rolling (Figure 5.2) This is attributed to the fact that the rolling load is higher in dry conditions due to a higher coefficient of friction [23]. The results of the tests show that both the roughness transfer ratio and the rolling force are significantly higher compared to oily conditions. Several researchers found similar outcomes. Kijima tested two materials in symmetrical rolling with rolls of various roughness levelsand two different lubricating oils: temper rolling oil and cold rolling oil [21]. The findings revealedthat the roughness transfer rate was greater under dry rolling conditions.

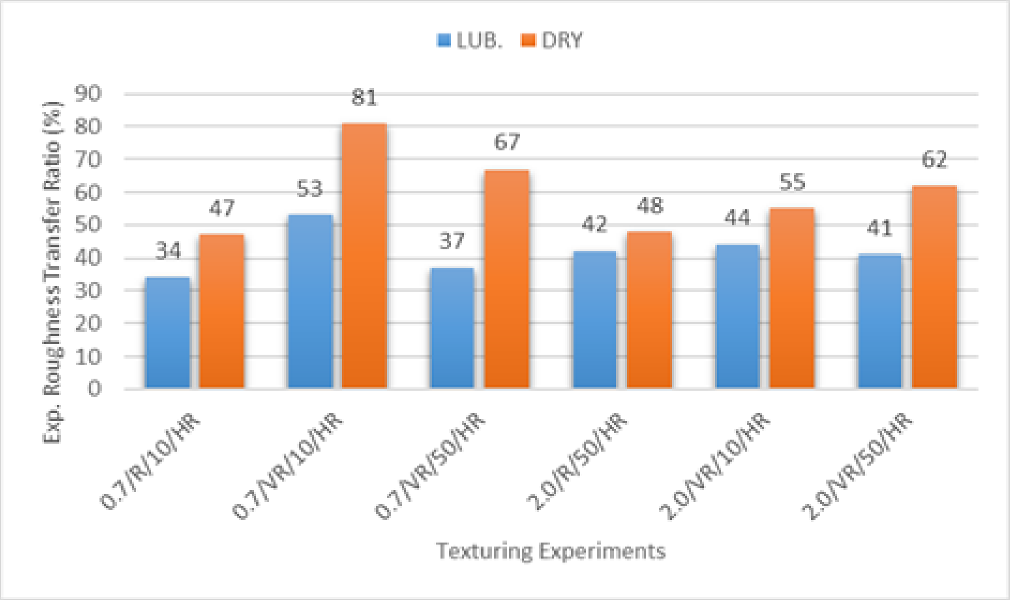


Figure 5.2. The influence of lubrication on RTR.

5.1.3. The Rolling Force Effect

The findings of thirty-two rolling tests using different variations demonstrate that roughness transfer rises as rolling force rises (Fig. 5.4). Also, other research by Bilal Çolak [22] shows that the transfer rate and rolling force had a direct relationship. High rolling loads develop when sharp peaks on the roughened roll surface are forced against the material surface with higherforce. Sharp peaks on the roll surface are in close contact with the material surface, where significant forces are produced. As a result, the peaks sink deeper into the material surface, producing deeper craters. Notably, testing below 2kN/mm rolling force results in a lower reduction, while tests above 2kN/mm rolling force result in a larger reduction (Fig. 5.3).

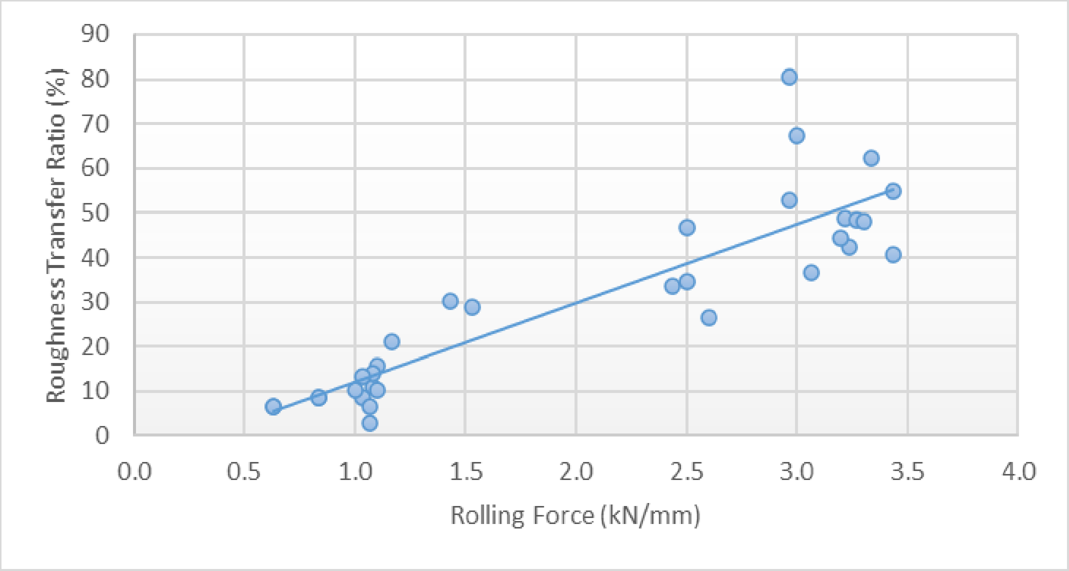


Figure 5.3. The rolling force effect on RTR.

5.2. Parameters Affecting Rolling Force

5.2.1. Material thickness

The rolling force is higher in thicker materials under the same conditions in AR (Fig. 5.4). Since the rolling force increases the transfer, it should be expected that the roughness transfer is higher in thicker materials. However, the rolling load was higher in thinner material in the CR process [22].

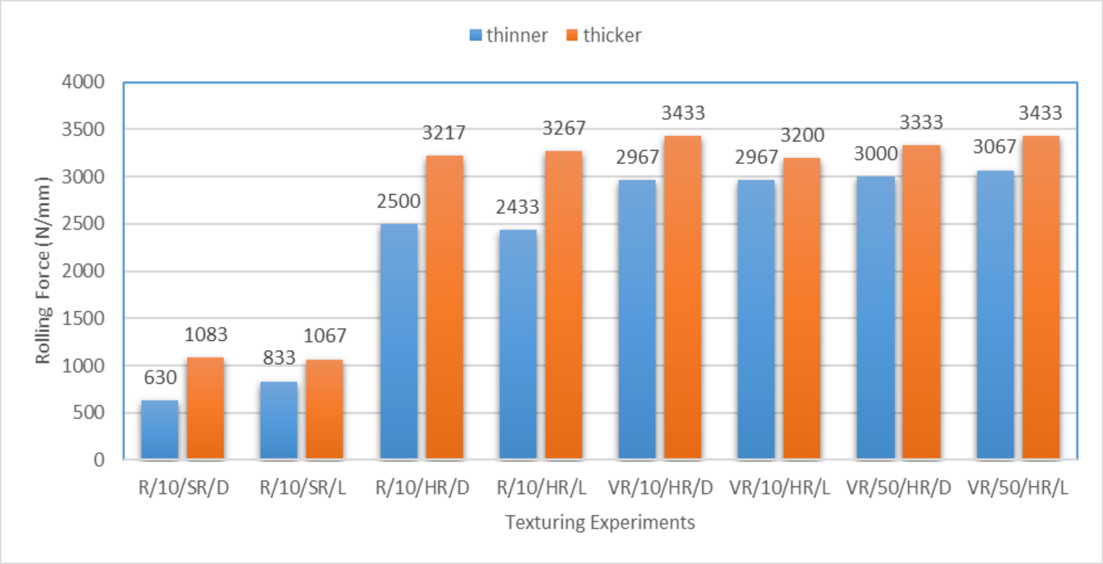


Figure 5.4. The material thickness effect on rolling force.

5.2.2. Rolling Speed

The rolling process involves a sheet's plastic deformation through the force generated by revolving rolls. As the sheet travels through a pair of rolls rotating in opposite directions, it undergoes plastic deformation beyond its yield strength. The speed at which the rolling process is performed can also significantly impact the rolling force. Increasing the rolling speed can lead to increased rolling force due to the increased material volume formed per unit of time. The experimental findings show that rolling force and speed have a direct proportional connection, as shown in Figure 5.5. This finding corresponds to previous research [22].

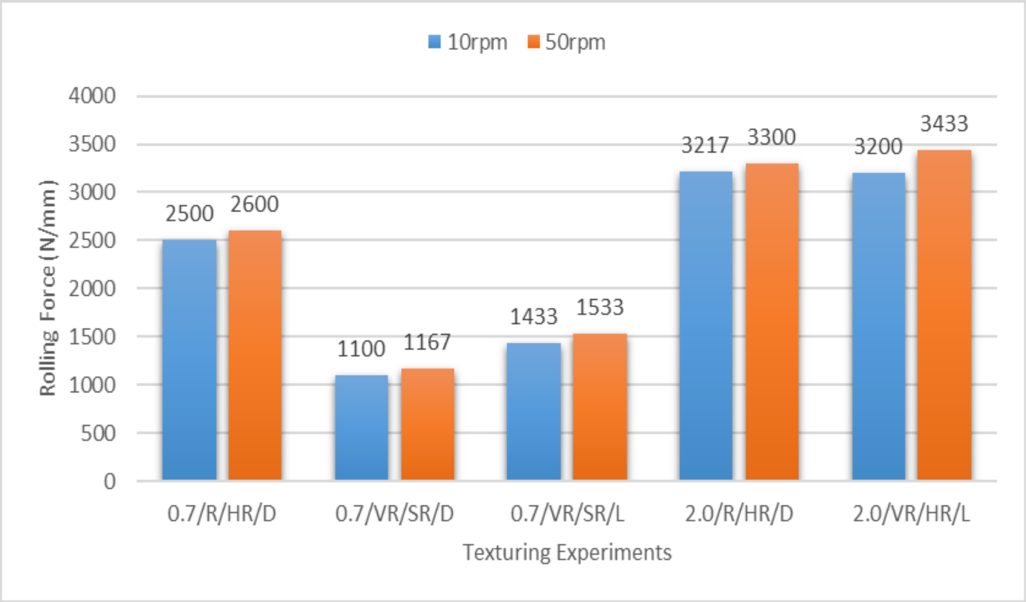


Figure 5.5. The speed effect on rolling force.

5.3. HOMOGENEITY OF THE SURFACE ROUGHNESS (STANDARD DEVIATION)

Multiple measurements from the test samples were taken to determine the arithmetic mean of roughness values (Ra). Obtaining this value for the visual quality of the dyed surface is usually insufficient. Furthermore, the roughness of the entire surface should vary within a narrow range. Roll surface roughness is vital in imparting these properties to a sheet surface [22] [24]. Even if the roll surface roughness is homogenous, it may not be enough to achieve a homogeneous roughness distribution on the material surface. Understanding and controlling any other factors that may impact on this is important. In an earlier investigation, several CR variations were investigated. The following are the ones in AR [22]. When the test results are compared between 10 and 50 rpm, the roughness distribution seems to occur in a narrow range.

5.3.1. The Effect of Reduction Ratio on Standard Deviation

It is clear from comparing the test results obtained at smaller reduction (SR) ratios to those obtainedat higher reduction (HR) ratios that testing utilizing rough rollers and extremely rough rolls achievea narrower range of roughness distribution at lower reduction ratios (as shown in Figure 5.6 and Figure 5.7 respectively). This finding is consistent with previous studies on symmetrical rolling [22]. However, the standard deviation is higher in the asymmetrical rolling tests performed with very rough rolls compared to the symmetrical rolling results (as depicted in Figure 5.8). This effectwas further visualized through 3D surface scans, with Figures 5.9a and 5.9b demonstrating 3D surface topography images for the tests conducted under 2.0/R/10/SR/L conditions in AR and CR,respectively. Upon comparison, it is evident that the symmetrical rolled surface has a more homogeneous roughness distribution than the asymmetrical rolled surface. These findings were confirmed by roughness measurement device readings, with a standard deviation of 0.08 in CR and 0.15 in AR. It is speculated that friction forces acting in opposite directions on both surfaces in the region between the neutral points during asymmetrical rolling can impair surface roughness.

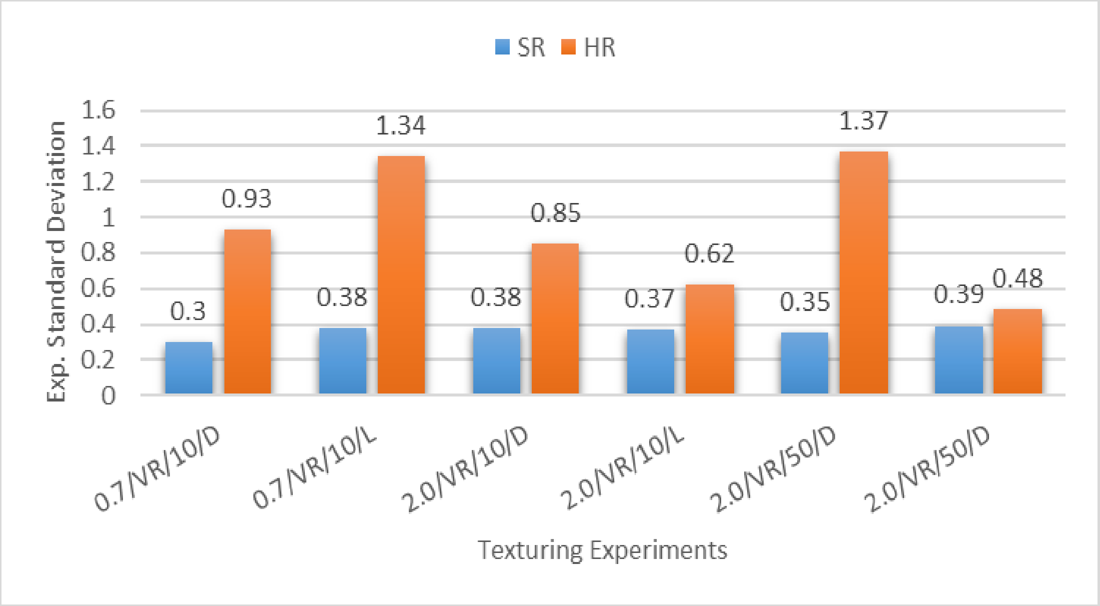


Figure 5.6. Experimental standard deviation (with rough roll-R).

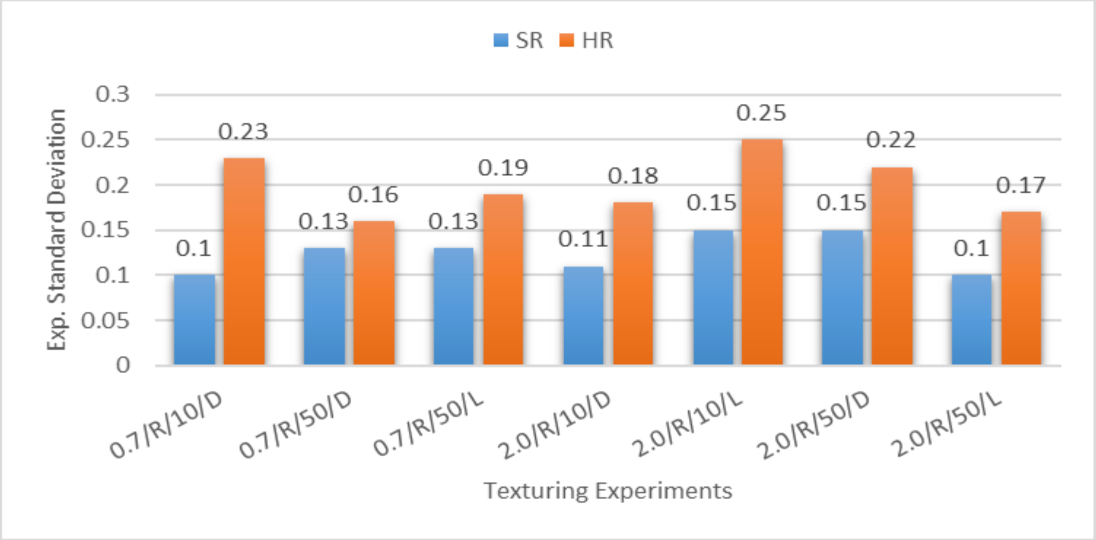


Figure 5.7. Experimental standard deviation (with very rough roll-VR).

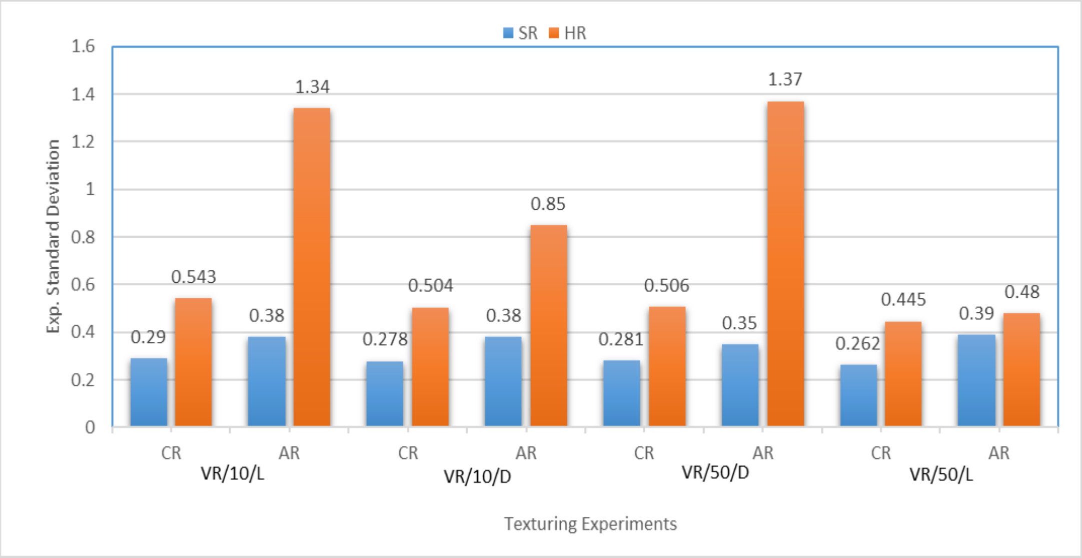
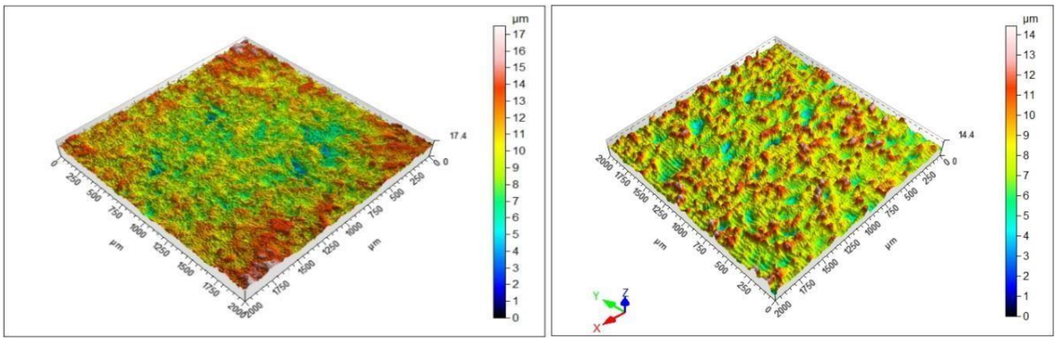


Figure 5.8. Comparison of standard deviation in CR and AR based on thickness reduction (CRdata is taken from another article [22]).



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

Figure 5.9. 3D optical field scan image for 2.0/R/10/SR/L conditions: (a) AR, and (b) CR.

5.3.2. The Effect of Lubrication on Standard Deviation

When we look at Figure 5.10 and Figure 5.11, 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 lubricatedrolling at higher speeds. However, in our previous study [22], the standard deviation was lower ateach speed value (lower or higher) in lubricated rolling. This can be attributed to the fact that whilethe hydrodynamic effect occurs at higher speeds in AR, this effect cannot be shown at lower speedsdespite the lubricant. This effect was visualized with 3D surface scans. Figures 5.12 show 3D surface topography images for the tests under 2.0/R/50/SR conditions. Comparing Figure 5.12a for dry AR with Figure 5.13b for lubricated AR, it is seen that the surface rolled with a lubricant has a more homogeneous roughness distribution at a higher speed (50rpm). The results measured manually from the material surface with the roughness measuring device are also in the same direction. The standard deviation was measured as 0.10 in lubricated rolling and 0.15 in dry rolling.Comparing Figure 5.12b with Figure 5.12c, showing the conventional rolled surface topography, it is seen that the symmetrical rolled surface has a more homogeneous roughness distribution than the asymmetrical rolled surface under lubricated conditions.

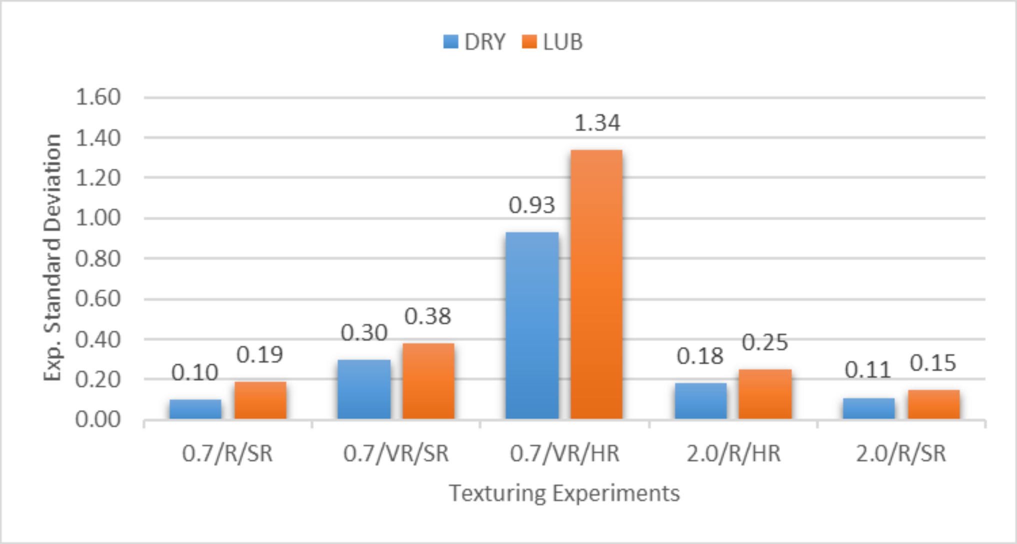


Figure 5.10. The effect of lubrication on standard deviation at low speed (10 rpm).

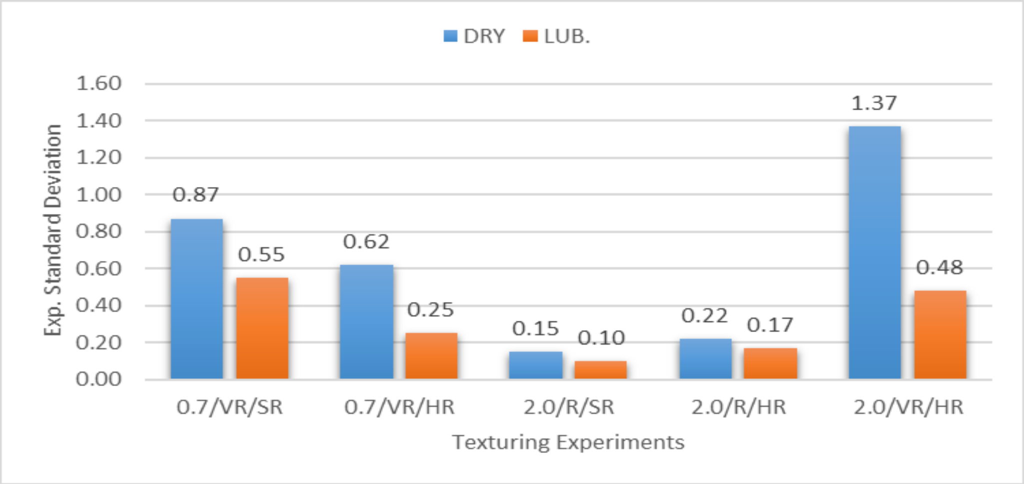
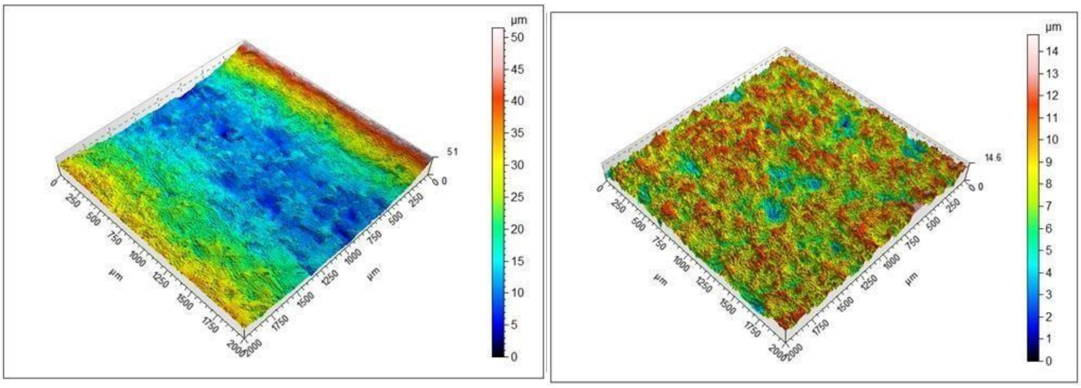
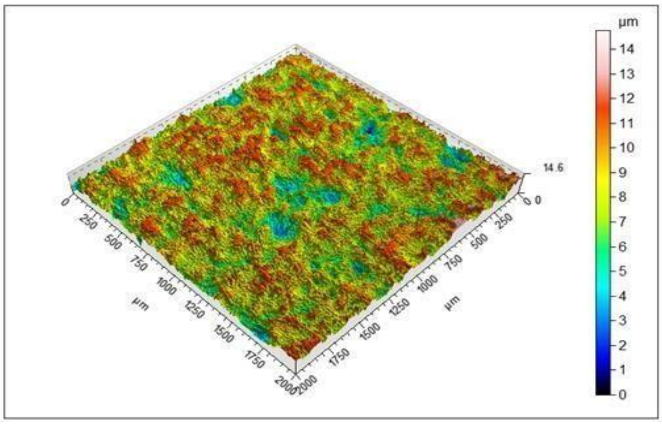


Figure 5.11. The effect of lubrication on standard deviation at high speed (50 rpm).



(a) Dry AR (standard deviation: 0.15)   (b) Lubricated AR (standard deviation: 0.10)

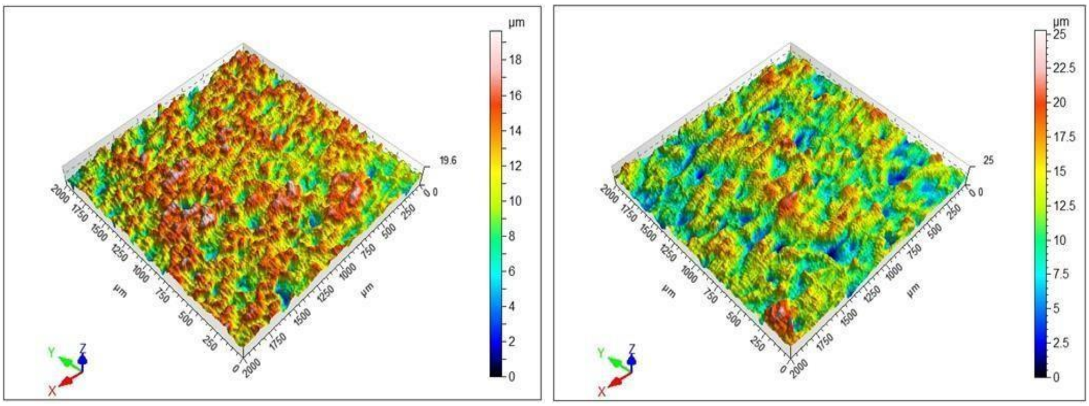


(c) Lubricated CR (standard deviation: 0.09)

Figure 5.12. Rolling under 2.0/R/50/SR conditions: (a) Dry AR, (b) Oily AR, and (c) Oily CR.

5.3.3. The Effect of Speed on Standard Deviation

In most of the AR tests performed at different speeds, it was observed that the roughness distribution changes 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 increasein AR (Fig. 5.13). The outcomes measured manually from the material surface with the roughnessmeasuring device are also in the same direction. The standard deviation measured is 0.17 at lowerspeeds and 0.22 at higher speeds. This was also the case in CR [22].



a) 10-rpm (standard deviation: 0.17) b) 50-rpm (standard deviation: 0.22)

Figure 5.13. 3D optical field scan images for 0.7/R/HR/D conditions at various speeds:(a) 10-rpm, and (b) 50-rpm.

When the tests' results were compared with those obtained in another study [22], it was found thatthe standard deviation was larger in AR under the same conditions. This is thought to be due to the greater sliding distance on the material surface due to asymmetrical conditions. This result shows that asymmetric rolling is unsuitable for producing materials with homogeneous surface roughness.

5.4. THE COMPLETE ANALYSIS OF EXPERIMENTS

The transfer of surface roughness from the rolls to the material during rolling is similar in Asymmetrical Rolling (AR) and Conventional Rolling-Symmetrical rolling (CR), as it increases with an increase in rolling force. However, a higher rolling force is required for thicker materials in AR, while a higher one is required for thinner materials in CR.

Moreover, the impact of roll roughness on the rolling force differs depending on the material's thickness. For thicker materials, the variation in the roughness of the rolls has a negligible effect on the rolling force. In contrast, using a very rough roll causes a more significant increase in rollingforce when rolling thinner materials than a rough roll would in the case of thicker materials. Therefore, when choosing the appropriate rolling method and roll roughness, the thickness of the material should also be considered to achieve the desired surface roughness.

Unlike conventional rolling (CR), surface roughness transfer decreases as the speed increases in Asymmetric rolled (AR). However, the rolling force, which typically leads to an increase in surfaceroughness transfer, decreases as the speed increases in AR. As a result, there are two opposing effects on the change in surface roughness transfer in AR with changing speed.

The roughness transfer is higher in dry rolling, and the standard deviation is lower at higher speedsand in oily conditions. This leads to the conclusion that lubricated AR is more suitable at higher speeds to achieve a more uniform distribution of roughness on the surface. However, it is essentialto note that the standard deviation in lubricated AR is larger than in lubricated symmetrical rolling.For rough and very rough rolls, the standard deviation is lower at lower thickness reduction but not as low as in CR.

To summarize, AR is known to have more significant effects on dislocation densities and grain size changes on the surface of the processed material than CR. This is advantageous when producing materials that require a hard surface but a ductile structure. Additionally, AR can provide higher strength on the material surface and requires lower rolling forces when performedunder similar conditions as CR.

PART 6

CONCLUSION

The purpose of this study was to experimentally investigate the effects of rolling parameters on roughness transfer in asymmetric rolling and to provide a deeper understanding of the mechanisms behind this phenomenon. Through a series of experiments and analysis of the resulting data, this study has shed light on the critical parameters that affect the roughness transfer process. The studyconcluded that the effects of rolling parameters on roughening characterization are below.

Lubricated roughening tests indicated that the roughness transfer is reduced due to lubrication. Furthermore, a more homogeneous roughness distribution was obtained in lubricated rolling compared to dry rolling at higher speeds, while it was acquired in dry rolling at lower speeds.

As the thickness reduction increases, the rolling force increases.

As the speed increases, although the rolling force, acts to increase the roughness transfer, the introduction of roughness decreases but the roughness distribution range increases.

The rolling force is higher when using thicker material than thinner material. While the rollroughness doesn't have much effect on the rolling force in the use of thicker material; it ishigher in the very rough roll compared to the rough roll when using thinner material. The standard deviation was lower in lower reduction ratios using rough and very rough rolls**.**

This experiment series aimed to offer guidance on parameter selection so that sheet metal producedthrough AR can have a good surface roughness. However, the test results showed that AR is not an excellent way to obtain a surface roughened sheet compared to CR.

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RESUME

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