

# **Surface Roughness, Hardness and Microstructure Characterization of Cold Rolled Sheet**

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In Partial Fulfilment of the Requirements  
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**Master of Engineering**  
**in**  
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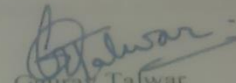
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**July, 2015**

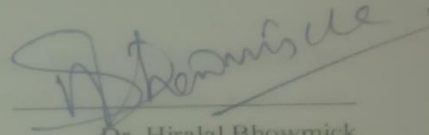
## CERTIFICATE

I hereby declare that the thesis entitled "Surface Roughness, Hardness and Micro Structure Characterization of Cold Rolled Sheet" is an authentic record of my study carried out as requirements for the award of the degree of Master of Engineering in Production Engineering at Thapar University, Patiala under the supervision of Dr. Hiralal Bhowmick, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during 22 July, 2013 to 15 July, 2015. The matter embodied in this report has not been submitted to any other university or institute for the award of any degree.

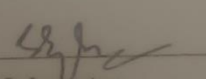
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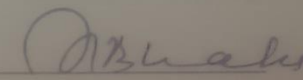
  
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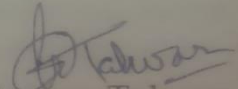
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# Abstract

Cold rolling process is the oldest deformation processes in metal-forming industry. Due to the ever increasing demand for high quality aluminum strips and foils, rolling lubrication and rolling oil are playing an important role in attaining the best possible rolled surface during the aluminum and steel cold rolling process. Surface roughness control is one of the most important subjects during producing steel and aluminium strips.

This research work is mainly pointed towards investigation of improvement in the surface features of cold rolling strips by using suitable lubricants. Thus, the effects of oil film on the rolled surface, including surface roughness, variation in rolling force and thickness reduction and rolled surface morphology, mechanical properties, etc, were investigated during cold rolling of aluminum and steel strips. Various lubricants with different viscosities were used for the study. The performance of water-based and mineral based lubricant is compared with rolling done without lubrication. It has been found from our work that more the viscosity of lubricant better is the quality of surface obtained after cold rolling.

Moreover, use of nanolubricants is rarely found in the literature for cold rolling process. Keeping in mind, the enhanced tribological and thermal characteristics of the selected nanoparticles, an attempt is also made to explore the impact of nanoparticles addition in the lubricant in the outcome of rolling process. Also, a theoretical analysis on strip surface roughness is carried out where experimental data are validated with an existing roughness model. A great number of statistical results show that experimental data is in excellent agreement with the adopted model and the relative deviation on roughness between calculated and measured is very less.

From the study it is also revealed that lubrication has significant impact on rolling outcome and surface features of rolled strips, including strip reduction and spreading of strip, amount surface transfer layer and surface roughness transfer and hardness of the rolled strips.

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## Nomenclature

$\mu\text{m}$	-Micrometer
mm	-Millimeter
nm	-Nano-meter
cst	-centistrokes
$R_a$	-Surface roughness
SEM	-Scanning Electron Microscopy
$\Delta h$	-Draft
$K_p$	-Constant of plasticity
$I_{Kp}$	-Index proportion
$R_a$ (Theoretical)	-Theoretical surface roughness
$R_a$ (Actual)	-Actual surface roughness measured
$R_a$ (New)	-Empirical surface roughness

# Chapter 1

## Introduction

---

### 1.1 Introduction

Rolling is a manufacturing process producing slab, sheet, strip and foil by deforming the metals plastically. Rolling was implemented for the production of steel in 1783 by Henry Cort, as Cort's first rolling mill, which consisted of grooved rollers, following which there has been a continuous development of the rolling mills. Modern mills have more sets of rollers, one above the other, and steel was rolled under continuous process through one set to another, and then reverse again, until the desired shape is obtained. It is one of the most widely used metals forming process due to its high production speed and accurate control of final product. Rolling plays a vital role in the production of steel for construction and industrial applications.

### 1.2 Rolling

Rolling is the sheet forming process in which work piece is plastically deformed by passing it through set of rollers. The process comprises of passing the metal from pair of rollers revolving with same speed but in opposite directions and separated so that the gap between them is less than the thickness of the sheet. Rolling is done to reduce the thickness of sheet by applying compressive forces. In this process the thickness of the slab is reduced to yield thinner product. Rolling is the process through which a uniform cross section is obtained along the full length of strip, [Chauhan *et al.*,2013]. Over 90% of the metals deformed by rolling process, [Schey , 1977]. Rolling is mainly categorized in two types i.e. cold and hot rolling process. Cold rolling process occurs below recrystallization temperature and hot rolling process is done above recrystallisation temperature. The temperature at which new set of strain free grains are formed is termed as recrystallisation temperature. In hot rolling, large deformation takes place; materials remain soft and ductile, hardness of the materials cannot be controlled after rolling and metal will experience oxidation resulting in material loss and poor surface finish.

Now-a-days, cold and hot rolling mills around the world are continuously looking for ways to increase their productivity, minimize energy consumption as well as improved quality of the

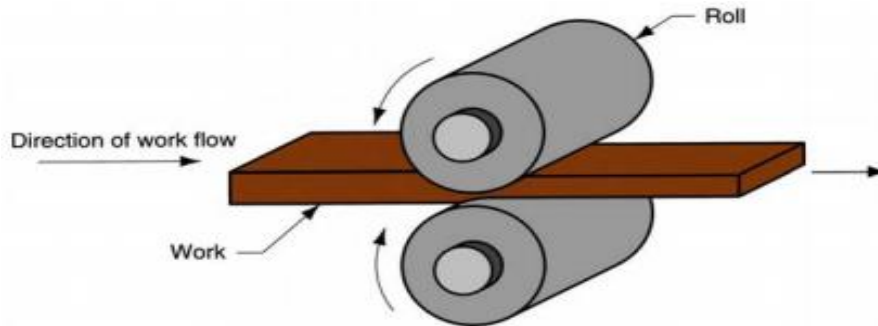
products. Use of effective lubrication in cold rolling and hot rolling are one of the most emerging way, the researchers all over the world, are attempting to implement for the above purpose. With the use of suitably designed lubrication system superior thickness tolerances and surface quality in cold rolling as well as reduced roll-wear can be achieved. However, nature of hot rolling is so complex that with many basic parameters not fully understood such as the interaction of the surfaces which depends upon so many factors such as process parameters, roll parameters, oxide types and characteristics, steel grades, etc, accurate investigation of friction and wear studies in the presence of lubrication is quite a daunting task. This is why, cold rolling is much preferred for the fundamental studies in lab scale. Cold rolled sheets are used in manufacturing of outer frame of ovens, water heaters, refrigerators. Cold rolled sheets of high strength steel are used in automobile body parts. Cold rolled sheets are used for beverages container and various kitchen equipment, [Kalpakjian , Schmid, 2014]. The present research work will focus on the cold rolling process and surface characterization of cold rolled strips. Thus, the following section gives a brief overview of the cold rolling process.

### **1.3 Cold rolling process**

Rolling at temperature lower than the recrystallisation of material is termed as cold rolling process. In this process metal strips are normally passed through set of rollers at room temperature. In cold rolling, lateral elongation of the strip is prevented by high transverse friction between the metal strip and rollers. Therefore width remains constant before and after rolling process. Cold-rolling, in which unheated bars, sheets, or strips are passed through the rollers, frequently requires numerous rolling to attain the desired shape. In cold rolling work material undergoes work hardening and to yield a product with a high-quality surface finish and improved mechanical properties annealing can be used in the final step of cold rolling process. Cold-rolled strips are widely used for motor vehicle bodies and domestic appliances.

This process changes various types of properties of work piece like morphological, micro-structural and other surface properties, [Degarmo *et al.*, 2003]. They offer better control of thickness, shape, width, surface finish, etc., which subsequently can be used for the emerging need for highly engineered end use applications. The full-hard level rolling decreases its thickness by 50% and skin-rolled reduces so by 0.5- 1%. In skin pass rolling, the final cold rolling process is used to process a strip surface with a defined surface roughness only. In this case a low very low reduction rate is used. This process has major effect on

increasing the yield strength of alloy, [Tajally *et al.*, 2009]. Through cold rolling better surface finish and tight dimensional tolerances are achieved.



**Fig 1.1 :** Schematic diagram of cold rolling

The following are the advantages of cold rolling:

- High dimensional accuracy is obtained.
- Superior surface finish.
- Least formation of scales ( least rapid oxidation).
- Improves strength/weight ratio.
- Improves the tensile strength and hardness of product, [Tajally *et al.*,2009].
- Enlargement of grains occurs in rolling direction, [Schindler *et al.*,2009].

The following are the disadvantages of cold rolling process:

- High intensity of forces are required for deformation.
- Powerful drives are required for cold rolling process.
- Chances of occurring strain hardening.
- Unwanted residual stresses may occur, so there are chances of heat treatment.
- Final product is prone to brittle fracture.
- Restricted to only ductile material

### **1.3.1 Cold rolling process equipment.**

Equipment for cold rolling process are customized depending upon percentage of reductions, presence of reversing or non reversing mills, etc. Basically rolling mills are classified on the basis of arrangement and number of rollers such as reversing and non-reversing 2-high rolling mills, 3 and 4-high rolling mills, tandem roll mills, cluster mills. Reversing mills are used for forward and backward motions and for heavy reductions.

In cold rolling process rollers are subjected to heavy operating conditions. Rollers materials are designed on the basis of bending strength, fatigue strength, torsional strength, wear resistance, hardness, yield strength, etc. Rolls in a rolling mill may be classified in a

number of ways. Rolls may be classified as their functions in mill, such as work rolls, backup rolls, process rolls and table rolls. They can also be classified as their materials of working surfaces, such as cast steel, forged steel, graphitic steel and cast iron. Besides, tungsten carbide coated, chromium plated and high speed steel rolls are also used for special purpose applications. Some rolling mills work on constant speed and some with variable speed i.e. with adjustable speeds.

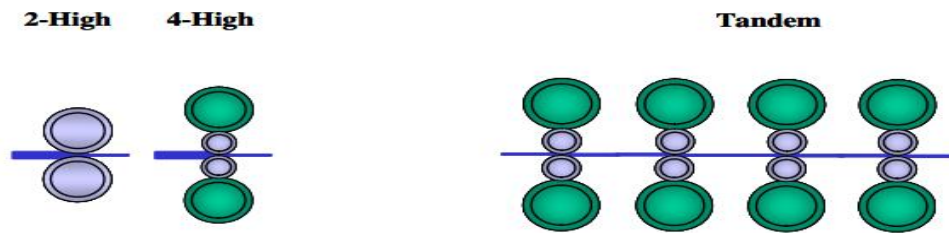


Fig 1.2: Types of rolling mills

### 1.3.2 Cold rolling process variables

The important process variables in cold rolling process include velocity of rollers, roller gap, number of passes, coefficient of friction. However, the effectiveness of the process also depends on surface quality of rollers and work piece, diameter of rollers and lubrication used. The effect of these process variables are determined through reduction in thickness and elongation in length achieved, surface and micro-structural characteristics obtained. Increase in reduction leads to significant increase in rolling force by which strip shape becomes poor, [Jiang *et al.*, 2009]. Rolling speed may increase or decrease the yield point of material. The following fish bone diagram, proposed by Valicek *et al.*, [2014] lists the most common factors which influence the properties of rolled products.

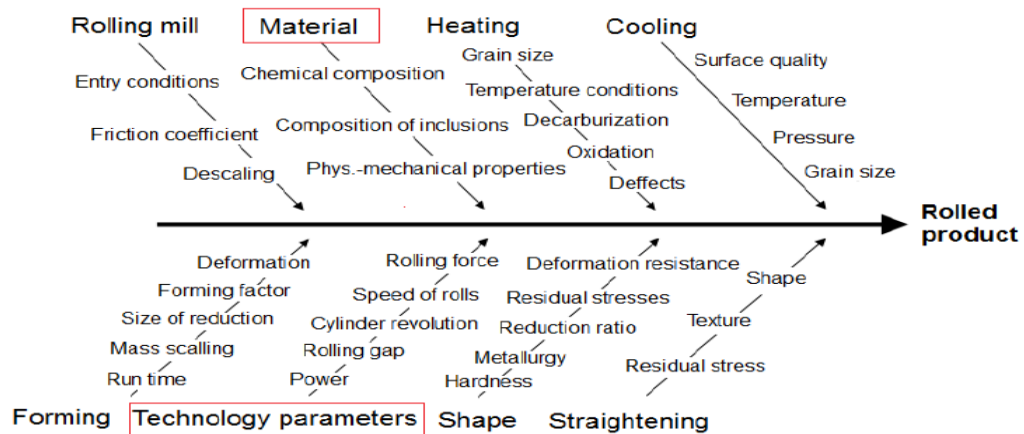


Fig 1.3: Fish bone diagram for cold rolling [Valicek *et al.*, 2014]

## **1.4 Lubrication used in cold rolling.**

Although it is possible to roll without lubrication, in most cold rolling operations, lubricant is used to reduce frictional forces, to protect the roll and strip surfaces, and to act as a coolant. Mostly in all metal forming processes major cause for lubricating cold rolling process is to manage friction and surface quality. In most conditions, steel and aluminum are lubricated in such a method that some asperities will contact and carry part of load, causing extra friction. Also, lesser the coefficient of friction lesser is the surface roughness, [Mazur, 2012].

Lubrication is used to decrease the friction, because rolling resistance which results from adhesive and deformation losses and can be minimized using suitable lubricants. Lubrication during cold rolling reduces the rolling loads and helps to obtain good surface quality by reducing the friction coefficient, wear and staining. It also helps in preventing direct contact between rollers and metal strips which further reduces chances of roughness transfer from rollers to metal piece [Plouraboue *et al.*, 1999]. Lubricant extracts heat produced by friction between rollers and work piece [Fosters *et al.*, 2011]. This process is done by using less viscous lubricants which includes low dense mineral oils [Kim *et al.*, 2012], water based oils, paraffin and fatty oils. Various emulsions may also be used.

## **1.5 Characterization of rolled strips**

The quality of machined surface is characterized by the accuracy of its manufacture with respect to the dimensions specified by the designer. Every machining operation leaves characteristic evidence on the machined surface. This evidence in the form of finely spaced micro irregularities left by the cutting tool. The various surface defects and structural defects of rolled surface include inclusions, impurities, scales, Roll marks, wavy edges, cracks, grain deformation, etc. Surface characterization is defined as the study of various features of surfaces like roughness, accuracy, surface morphology, grain size etc.

### **1.5.1 Surface roughness**

Each type of cutting tool leaves its own individual pattern which therefore can be identified. This pattern is known as surface finish or surface roughness. Surface roughness indicates the state of a machined surface. In practice both the roll and the strip surfaces are rough. During cold strip rolling, at areas of contact between the roll and strip, surface flattening occurs as the hard roll flattens the softer work piece asperities. In the valley regions surface roughening can occur due to inhomogeneous deformation associated with the crystal structure of the metal.

In many rolling processes, the roll grinding process leads to a roll roughness with a pronounced lay, with asperities running along the rolling direction. This longitudinal roughness is in turn transferred to the strip. Isotropic roughness is also common, for example where the surface has been produced by shot blasting, while transverse roughness, with asperities running perpendicular to the rolling direction, seems to be less common. Surface roughness plays an important role in cold rolling either rolling done with lubrication or without lubrication. Roughness is nothing but irregularities. Such irregularities combine to form texture of surface. It affects various functional attributes of parts like friction, ability to hold and spread lubricant on surface, heat transfer etc. Hence surface roughness of strip is very important to judge the quality of strip. Roughness can also be termed as height of unevenness [Barbulovic *et al.*,2003]. Generally both the roller surface and strip are rough, which leads to roughness transfer phenomenon [ Lenard , 2004 ]. Various authors have studied the effect of lubrication on surface quality by cold rolling process.

Most commonly used roughness parameters are:

*Average Roughness ( $R_a$ ):* It is the arithmetic average of absolute roughness values.

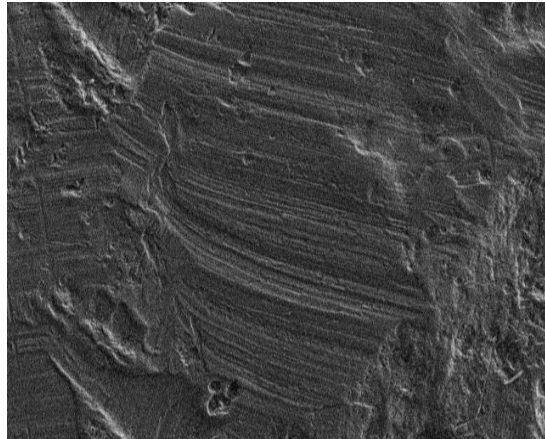
*Root Mean Square Roughness ( $R_q$ ):* It is the root mean square average of roughness values.

$R_q$  is much more sensitive to roughness values than  $R_a$  because amplitudes get squared.

Measurements of surface finish in rolling are relatively easy to obtain. Rolled strip or lab samples can be used to measure surface finish on a profilometer. A comprehensive review of profilometry methods. Careful judgment needs to be made about appropriate filtering, to eliminate long wavelength components associated with roll form error or lack of flatness in the samples while extracting data obtained from the profilometry. Modern three-dimensional profilometer give valuable additional information about the shape of the surface topographic features. Images using a scanning electron microscope (SEM) are also essential to confirm that the mechanisms of friction are similar to those found in the corresponding industrial application.

### **1.5.2 Morphology**

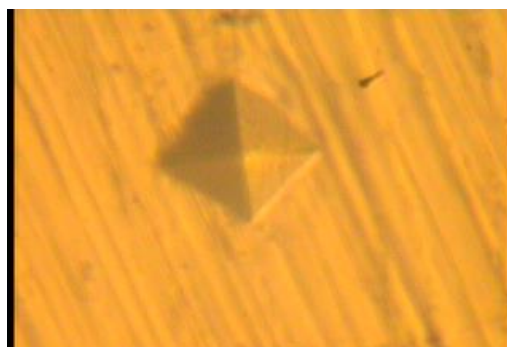
Morphological characterization has received the wide attention to characterize the effect of processing on surface [Liu *et al.*, 2010] of cold rolled strips. The main goal of morphology study is to describe the surface quality using microscopic views which is done either by optical microscope, SEM or TEM. With the help of metallurgical microscope magnified images of surface is observed and on the basis of these views surface characterizations are made.



**Fig 1.4:** Surface of cold rolled metal strip

### **1.5.3 Micro hardness**

The term micro hardness test usually refers to static indentations made with loads not exceeding 1 kgf. The indenter is either the Vickers diamond pyramid or the Knoop elongated diamond pyramid. In this, the hardness of the material is characterized on microscopic scale. The testing procedure is similar to Vicker's hardness test, except that it is done on a microscopic scale with higher precision instruments. The surface being tested generally requires a metallographic finish so that indentation can be easily visualized; the smaller the load used, the higher the surface finish required. In this high precision microscopes are used to measure the indentations, usually with a magnification of around x500 and measure to an accuracy of +0.5 micrometres. It should, however, be added that considerable care and experience are necessary to obtain this accuracy.



**Fig 1.5:** Micro hardness indenter

### **1.5.3 Micro structure**

While depicting the structure of substance, a clear distinction is made between its crystal structure and its microstructure. Micro structure is defined as “The arrangement of phases and defects within a material.”



**Fig 1.6:** Micro structural view

Numerous methods are applicable to study, compare, describe and quantify the microstructures in substances. Optical microscopy, transmission electron microscopy, scanning electron microscopy are instruments used to examine the microstructures. Various factors are engaged to explain the microstructures. These include the following:

- Grain size
- Grain shape and distribution
- Inter-particle spacing
- Volume fraction of precipitates
- Dislocation type
- Density

# Chapter 2

## Literature Review

---

### 2.1 Introduction

Rolling is process of reducing thickness or altering cross section through compressive forces applied by set of rollers. Cold rolling is frequently implemented to produce metal pieces with fine thickness, surface quality. This chapter deals with an extensive literature surveys of the work on cold rolling process done with and without lubrication, carried out by the various researchers around worldwide.

### 2.2 Literature survey

**Kenmoch et al., [1990]** have analyzed impact of micro-defects on surface brightness on steel piece which has been cold rolled. To analyze this effect, cold rolling experiment was conducted with roll diameter of 530 mm. Micro-defects were analyzed by optical microscope and scanning electron microscopy (SEM), and differentiated according to shapes. Micro-defects are micro-pits origins by surface roughness and remain on the surface of cold-rolled material. From the finding of their work they concluded that surface brightness can be judged strongly by micro defects and brightness can be enhanced with lessening surface-area ratio of micro-defects. They categorized the micro-defects into four types; micro-pits coming from surface roughness of parent sheet; oil-pits created during cold rolling; grooves created by inter-granular corrosion through pickling; and scratches due to surface roughness of rolls.

They also found that micro-pits left over on surface of cold rolled sheet were affected with roller diameter, surface roughness of parent sheet, and rolling reduction with the insignificant effect of rolling speed and of viscosity of rolling oil were minor.

**Flouraboue et al.[1997]** have examined surface roughness shift from steel roller to Al alloy piece. Three unlike samples were collected i.e. (sample rolled on industrial mill, industrial rolled sample once rolled on laboratory mill and additional laboratory rolled industrial sample). Every sample was lubricated with special oil consist of lauric alcohol, isostearic acid before proceeding for rolling. Before measuring surface roughness samples were cleaned using hexane. It was found that roughness transfer affects multi scale properties. It was established that both rolled aluminium alloy sheet and roller surfaces are anisotropic self-

affine surfaces with very alike properties. They concluded in both transverse and longitudinal order rough exponents and amplitudes and found dissimilarity among longitudinal rough exponents of sheets and rollers. In addition, they had monitored that this difference is decreased through rolling pass.

**Montmitonnet et al., [1999]** explains transfer layer in cold metal piece rolling method. Due to irregularity of mechanical properties among work pieces and tools, yet transfer layers are much more common. A range of metals and alloys had been studied by them under a range of deformation conditions. Various types of transfer layers were established in rolling depending on alloy and rolling environments.

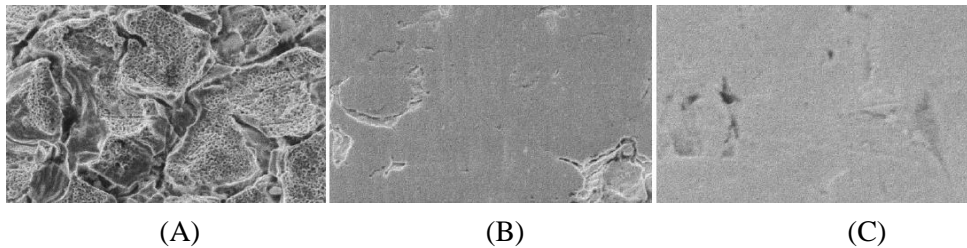
**Le et al., [1999]**, in their paper carried out a detailed investigation of surface finish of aluminium thin piece and foil which had been cold rolled in industrial conditions under mixed lubrication regime condition. A coil of aluminium alloy with initial piece of thickness 0.4 mm was rolled in industrial condition at steady speed for 1<sup>st</sup> pass and at a broad variety of speeds for second pass. Decrease in thickness during both passes was around 50 percent. Lubricant was applied on both sides of piece. Samples were collected after rolling with worn rolls.

Their results had shown that roughness on bottom surface of initial piece is much greater than on top surface. It was also concluded that surface roughness measurements on aluminium foil rolled in industrial condition demonstrate that surface of piece almost conforms to roller surface after first pass. Following passes to some extent reduce surface roughness on piece. Also, spectral analysis ensured that long wavelength components on piece surface are compressed more easily than short wavelength components.

**Sutcliffe et al., [2000]** have depicted the measurements of alter in surface roughness of aluminium due to cold rolling. Mostly of experimental facts are for unlubricated rolling experiment. Only major alter in method was in inclusion of a lubricant. Roughness of pieces was calculated with diamond-stylus profilometer at traverse speed of 0.3 mm/s. Roller roughness was calculated from an acetate impression of roller. Spectra of roughness for initial and final rolled surfaces were used to take out amplitudes for long and short wavelength components. It was revealed that short wavelength components keep on more than long wavelength components, flattening of piece raise with decline in piece thickness.

**Ahmed et al., [2000]** performed experiments to recognize surface quality on cold-rolled stainless steel piece. The target of research was to identify pit marks on roller and pieces. Samples of various austenitic stainless steel sheets were collected at various intermediate stages of the manufacturing processes. The hot band was annealed, shot-blasted and pickled.

It was concluded with several pass of piece from the rolling machine, surface features get improved and surface roughness decreases. During rolling, roll marks also transferred to the piece to leave a surface finish on the piece, as illustrated in the optical micrograph, which is undesirable.



**Fig 2.1:** Micrographs of the sheet surface after various passes:

(A) The shot-blast and pickled surface; (B) After an intermediate pass; (C) After the final pass [Ahmed *et al.*, 2000]

**Ahmed et al., [2001]** investigated the mechanisms of pit removal in rolling of stainless steel piece. Samples got from an industrial rolling machine. Samples of stainless steel sheet of width 1.3 m and initial thickness 4.0 mm. Work rollers used for passes, were around 50 mm in diameter and were viewed after first pass to  $R_q$  roughness of about  $0.15\mu\text{m}$ . To validate pit evolution in cold rolling, three unlike mineral oil lubricants were used, namely a gear oil, a thinner general purpose oil Vitrea 68, rolling oil Genrex-H12. It was concluded that the lubricant reduce the rate of crushing artificial indents on a even surface and rough shot-blast surface through plane strain compression tests, ensuring the role of hydrostatic pressure in preventing pit removal. Variation of pit area and  $R_q$  roughness with overall reduction was similar for piece-drawn and cold-rolled stainless steel samples.

**Henian [2001]** performed the research and use of rolling oil for stainless sheet steel. Cold rolling of steel sheets was done on SENDZIMIR 20 rolls high speed rolling machine. Mobil Genrex 26 was used as lubricating oil. The cold rolling oil for stainless sheet steel was formed by Lanzhou Lubricating Oils Research and Develop Center. The outcome specified that lubricating oil must have fine properties of anti-wear, oxidation, emulsifying and fine rust-preventing characteristics. Also, it was concluded that the cold rolling oils for stainless sheet steel is metal forming oil by purpose of lubricating, washing and cooling.

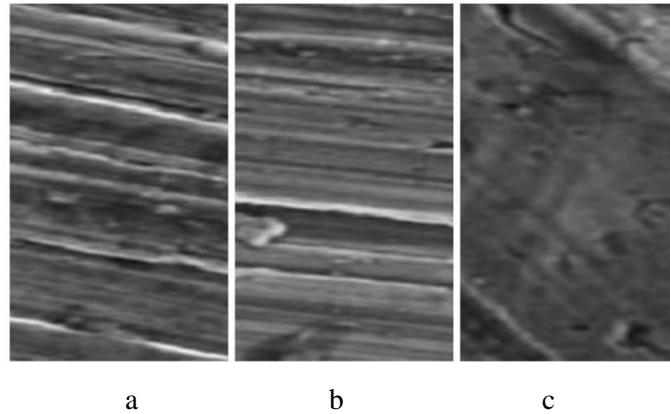
**Ma et al. [2002]** explained that surface roughness transfer in cold rolling process of carbon steel pieces. An experimental investigation of surface transfer in cold rolling of carbon steel piece and influence of rolling parameters was carried out by them. They emphasized that to get a further correct model for rolling process an essential aspect is to expect friction between roll and steel piece and result of lubricants. A sequence of experiments with a variety of roll

surface roughness, reduction, speed and lubrication had been conducted on a laboratory rolling machine. Their experiment process consisted of two steps i.e. rolling experiments, and calculation of surface roughness. Industrial hot-rolled carbon steel piece through a skin-pass finishing was cut into small samples by size of 2 mm thick, 75 mm wide and 1200 mm long. Samples were rolled on two high laboratory rolling machine.

Measurement of surface roughness of rollers was calculated by a portable roughness tester previous to every pass. An AFM formed by Digital Instruments, with a lateral resolution of 1–5 nm and vertical resolution of 0.08 nm was used to calculate surface of steel samples before and after every rolling experiment. Sample dimension is restricted to 12 mm square. A measurement by a standard diamond stylus profilometer shows that longest wavelength on steel samples is around 100 nm. Results got from this research were very dissimilar from outcome obtained from cold rolled Al pieces. As steel is harder than Al pieces and also during cold rolling there is not at all formation oxide layer on steel strip because heat generation is very less in cold rolling which leads to sticking phenomenon and surface gets poorer. Surface roughness increases with enhance in rolling speed and reduction. Smooth surface is obtained in low reduction.

**Tahir et al., [2003]** had carried out a study on the impact of lubrication and roller wear in rolling machines. In their study, lubrication performance of some recently found water-based synthetic lubricants was compared with at present used mineral oils and emulsions. A synthetic water-based lubricant, applied in cold rolling of Al- alloy, demonstrated fine lubrication ability than mineral oil but poorer than emulsion. Rolled Al piece finish was got to be best for synthetic lubricant than mineral oil and emulsion.

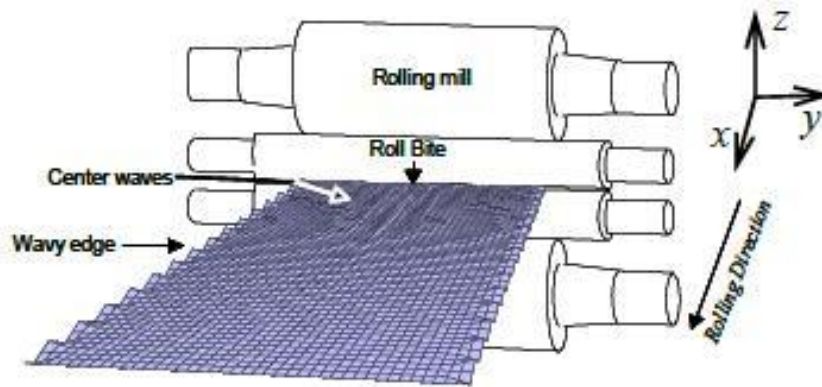
**Lenard et al., [2004]** explained the influence of viscosity of lubricant on roughness of cold rolled steel pieces. The mechanisms of three available oil-in-water emulsions were investigated throughout cold rolling carbon steel pieces. It was accomplished that roll roughness plays an essential role affecting the relevant rolling parameters throughout cold rolling of steel pieces. As likely, bigger roughness leads to rise in the loads on the rolling mill. Effective lubrication is vital to manage the tribological relations between the work rollers and the work piece in the cold rolling process. Three lubricants of dissimilar viscosity were used. It was accomplished that larger the viscosity of oil a lesser amount is the surface roughness.



**Fig 2.2:** SEM micrographs of the piece surfaces, obtained using the emulsions containing the lowest and highest viscosity oil [Lenard *et al.*, 2004]

**Tieu et al. [2006]** explained workings of roll edge contact in cold rolling of thin piece. Roll edge contact means contact taking place between lower and upper rollers. Cold rolling of thin piece due to roll edge contact with oil lubrication and linked surface roughness was investigated in research. Surface roughness and asperity of rolled piece were characterized by surface profilometer and AFM. They developed a customized influence function method and its numerical simulation code to analyze the rolling force, intermediate force between work roller and backup roller, edge contact force, piece shape and profile following rolling and length of roll edge contact for cold rolling of thin piece. Their research signifies that surface roughness decreases with a more reduction or rolling speed. Outcome of piece width on surface roughness was not noteworthy. Calculated rolling force, intermediate force and work roller edge contact force raise extensively when reduction enhances. Strip profile becomes worse with a elevated reduction.

**Abdelkhalek et al [2008]** explained the mechanism of flatness defects in thin plates which come into view during rolling. Flatness defects are one of the major problems faced in piece rolling. The authors reasoned that it causes due to the roll stack thermo-elastic deformation and out-of bite stress gradients resulting in buckling in the stress regions. Thermo-elastic deformation means grouping of elastic deflection and thermal effect formed because of compressive plus tensile stress. They also observed that defects are usually non-symmetric, neither in the vertical nor in the transverse way.



**Fig 2.3:** Schematic illustration of flatness defects [Abdelkhalek *et al.*, 2008]

**Jiang et al. [2009]** theoretically analysed the cold rolling of ultra thin steel piece with edge rolling. Edge Rolling means extra rollers used in the process so to get min. alter in width of the piece. It was proved that surface roughness of steel is reduced with raise in reduction of thickness of piece. Also, it was observed that edge roll force helps in improving the surface accuracy and surface roughness.

**Lu et al., [2009]** examined the effect of surface roughness on lubrication in cold rolling of metals. In this article experiments were conducted on a laboratory rolling mill to evaluate the effects of surface roughness on lubrication in the cold rolling of thin steel and aluminum pieces. Positive lubricating conditions were established as the initial piece surface had well-built transverse directionality due to simplicity of moving lubricant into the roller gap and configuration of oil pockets on the piece surface. It was found that rough marks on rollers and strips are excepted because they act as reservoir for lubricating oil but beyond certain limit it increases the surface layer transfer phenomenon.

**Adeosun et al., [2011]** explains the outcome of deformation on hardness of aluminum 6063 alloy. Cast trial samples were cold rolled in range of 0-24 % thickness reduction. Cast samples were machined to 200×30×9 mm and 100×25×9 mm for collective and non collective thickness reduction correspondingly. The samples were rolled at ambient temperature, 25<sup>0</sup>C, by a four-high mill associated with thickness reduction changeable from 0 to 24 %. Distorted samples hardness was examined by Rockwell Hardness tester. Cold rolled samples were all set for photomicrographic test by sequential polishing by means of emery paper grade 80,220,320 and 600 micron in series. Etching of samples intended for 20 seconds was made by means of a mixture of dilute nitric acid (68%), and sodium hydroxide (2%), hydrofluoric acid (30%). Photo micrographs of sample were taken at ×200 magnification. Outcome illustrated important enhancement in hardness. Hardness of test samples raised

almost linearly firstly within 0-8 % thickness reductions while there was no major rise in hardness among 8 and 14 % thickness reduction. At 15 % and further, hardness value enlarged steadily to highest value. Their research revealed that cold rolling of 6063 Al alloy effects major impact on its mechanical features. It has been revealed that hardness improved from 0 to 24 % thickness reduction.

**Napel et al., [2011]** carried out their research on the implementation of lubrication in cold rolling. In that study a model was proposed for the lubrication in cold rolling. Mainly in aluminum foil rolling, somewhere piece is very thin and material is comparatively soft, the surface quality is entirely estimated by lubrication process.

**Mazur [2012]** explained the phase of cold rolling that influences the surface superiority of final piece. Hypothetical and experimental outcome, as well as practice in the production of thin steel sheet at a range of activity, exposes the features of cold rolling and trimming that influence surface quality of final piece. In their trials emulsion lubricants was used. Means of assembling current condition on surface roughness of steel sheet were analysed. There are parameters which depicted for key concern in ensuring particular surface roughness. Skin Pass Rolling is a light cold rolling method that is in use to recover flatness and generate fine surface. In this study it was establish that raise in both rolling speed and temperature may amplify or diminish the yield point. Reduction in frictional coefficient in rolling and temper rolling reduces roughness. Lubrication assists in improving surface characteristics and lessen roughness. With the use of emulsion lubricant it was found that amount of roller roughness to piece is reduced by 10%.

**Yizhu et al., [2012]** done research on lubrication behaviors of nano-copper mixed in lubricant for piece cold rolling. In this experimentation nano-Cu particles of normal size smaller than 20 nm were isolated in lubricant by graphite stirrer. Investigation outcome revealed the fact that nano-Cu particles as chemical addition used in cold rolling lubricant were capable to progress the friction-reducing, anti-wear, and extreme pressure feat of base stock considerably. At similar time, nano-Cu particles too demonstrated fine lubricity to cold-rolled steel pieces. Namely, cold-rolled steel pieces in lubrication of cold rolling lubricant including nano-Cu particles had significantly reduced after-rolling thickness and attained outstanding surface quality as well.

**Foster et al. [2013]** concluded lubrication is an essential part of all aluminum fabricating operations, either directly through the metal working processes, or indirectly to lubricate machinery. This experimental study concluded that for all types of aluminum rolling the role of the lubricant is threefold: to prevent direct contact between the roll and aluminum surfaces,

to extract the heat generated by friction and deformation and to take away fines and debris from the roll bite area to the filter.

**Hallberg [2013]** explains the evolution of microstructure during cold rolling of AA1050 aluminum. Grain size evolution due to dynamic recrystallization was measured. Impact of process factors such as rolling friction, thickness reduction in every rolling pass and amount of rolling asymmetry were examined. Their study shown that grain refinement because of dynamic recrystallization is mainly affected by quantity of thickness reduction in each pass and intensity of rolling friction and to a smaller point by asymmetry of rolling process. Rising degree of asymmetry will, but lessen its dissimilarity in grain size during sheet thickness and disappear the material further homogeneously recrystallized. Grain size lessening during dynamic recrystallization is determined by plastic deformation and finer grain sizes can be predictable as level of asymmetry is enlarged. It is also manifested that quantity of plastic deformation attained in recreation is extra impacted by addition a second rolling pass than by growing rolling asymmetry.

## **2.3 Summary of literature review**

This review is mainly focused on cold rolling of strips. Many authors made conclusions on post effects of cold rolling process like surface roughness, surface morphology, flatness, hardness etc. Prime objective of entire research done by the majority of the investigators are aimed at improving the above mentioned post effects of cold rolling. After the study of literature review, it is observed that there are many major factors which affect directly and indirectly to the surface of the roll mill & work sheet. Along with cold rolling factors, pressure distribution, forces or friction hill contained by roll gap is main factor. Amongst all of the earlier works in this aspect are based on laboratory simulations relatively than industrial mill circumstances though situation can be completely different. Surface features are measured and it is revealed that steel surface roughness diminish with an raise in reduction. Efficient lubrication arrangement is essential for attaining these goals.

## **2.4 Gaps in the reviewed literature**

From the above literature survey on cold rolling, the following gaps are figured out.

- Despite of being wide applicability, aluminium and its alloys whose roughness reduction is not so easy, are less explored.
- Very few studies are done in the field of use of nano-sized particles used in lubricant to

improve the surface finish of work materials in cold rolling.

- Although some mathematical modelings are presented in the form of empirical and semi-empirical form to relate friction and surface roughness along with the other process parameters rarely anybody had directly explored the effect of lubrication on the surface finish of the rolled materials. So further study is possible in this case.
- Further studies are possible to design suitable lubrication package for cold rolling processes.

## **2.5 Scope and objective of the study**

From the above mentioned gaps it can be observed that further work can be performed on the process parameters for improving surface quality and surface features of cold rolled pieces. The scope and the requirement for this study can be well explained by understanding application areas of Al alloys and steel. In cold rolling material experiences work hardening and can be used to enhance mechanical properties of piece, to yield a product with a high-quality surface finish. So in order to improve its surface quality as well as mechanical properties cold rolling method with suitable lubricants can be implemented.

This research study will help in understanding following issues:

- The influence of contact conditions in improving the surface quality of aluminium and steel metals.
- Selection of suitable lubricants for cold rolling application
- It will also investigate the feasibility and impact of the use of nano-sized particles in lubricant on the improvement of the surface finish of work materials in cold rolling.
- Comparison of surface roughness models in dry and wet rolling

# Chapter 3

## Methodology

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### 3.1 Introduction

This chapter discusses the detail outline of the overall design of the study which includes methodology, experimental procedure followed, details of machines, equipment and the software used.

### 3.2 Roll strip materials

#### 3.2.1 Mild Steel [AISI 1052]

It is the general type of steel due to its cheap price and it grant material properties which are applicable for numerous applications. Low carbon steel consists of nearly 0.05-0.15% carbon. It has good ductility, toughness and easily machinable. Table 3.1 presents the chemical composition of the above mentioned metals. Chemical composition of mild steel was obtained from the spectroscopy of mild steel sample done at Thapar University, Patiala.

**Table 3.1:** Chemical composition of mild steel

C	Si	Mn	P	S	Cr	Ni	Cu	V	Fe
0.500	0.11	1.06	0.069	0.050	0.043	0.304	1.80	0.038	Balance

#### 3.2.2 Aluminium

Aluminium is most often used non ferrous metal. It is the metal with less density and it has the ability to resist corrosion. Aluminium is silvery-white in color, lightweight, soft and malleable, etc. It has vital role in the field of structural material, transportation and aerospace industries. Aluminium has many industrial and day to day need applications, which includes but not limited to beverages cans industry, foils and kitchen utensils manufacturing, manufacturing of electrical transmission lines, etc. The materials used for the experimentation is aluminium alloy (AA6101). Table 3.2 presents the chemical composition of the selected alloy.

**Table 3.2:** Chemical composition of AA6101

Zn	Mn	Cu	Mg	Si	Fe	Cr	Al
0.10	0.03	0.10	0.39	0.37	0.25	0.03	Balance

### 3.3 Lubricating oils

Two type of lubricating oils were used in order to compare the surface properties and qualities of metal strips i.e. water based oil and mineral based oil. Besides, a nano-clay is also explored for the study.

**Mineral oil:** Servoarol Light is finest class low viscosity straight mineral oil, particularly made for cold rolling process without upsetting gauge accuracy and applicable for both ferrous and non-ferrous metals. Its slight boiling range and elevated IBP decrease the rate of evaporation thus bringing downward the roll coolant use. It has inbuilt oiliness property to lessen the friction; help out metal reduction without allowing slippage. It is neither staining nor corrosive and has fine additive solubility for alcohols and fats which are supplemented by the producers of aluminium for manufacturing compensation.

**Table 3.3:** Features of Servorol light [<https://www.iocl.com/products/LubesGreases.aspx>]

Properties	Values
Viscosity at 40 C, cst	24
Flash point ( °C ), COC	160

**Water based oil:** Servosteerol C 4 is a finest quality oil-in-water type fluid, suggested for cold rolling of ferrous and non ferrous metals. This oil outlines a steady and extensive lasting emulsion with water and has outstanding cooling and friction lessening properties whose outcome is improved life of roller, less power consumption and improved production. The ratio of oil in water used for experiments is 1:2 i.e. one part of oil and two part of water by volume.

**Table 3.4:** Features of Servosteerol C4 [<https://www.iocl.com/products/LubesGreases.aspx>]

Properties	Values
Viscosity at 40 C, cst	25
Flash point ( °C ), COC	170



**Fig 3.1** : Mineral based oil (Servorol Light)



**Fig 3.2** : Water based oil (Servosteerol C 4)

[Photo Courtesy: Thapar University campus, Patiala]

**Nano clay particles:** The clay used is the *Cloisite*® 93A, which is a natural montmorillonite used as an additive used to improve various properties. Following table shows the properties of the selected nanoparticle.

**Table 3.5:** Properties of *Cloisite*® 93A

[<http://www.nanoshel.com/product/cloisite-93a-montmorillonite-nano-powderspurity-99-aps/>]

Color	Off White
Particle Size	<80nm
MOHS Hardness	5.5
Density	2.86g/cc
pH	8–9

### 3.4 Rolling mill

The machine used for rolling experiment consists of fixed top roll and adjustable bottom roller. It's two mill high reversing. The machine body is all steel welded construction. The rolling machine drive is a collaboration of electro-mechanical drive with oil cooled gearbox & hydraulic power pack. Rolls are made from En-8 forged steel. The machine has a semi centralized lubrication system. Specification of machine is described in below table :-

**Table 3.6:** Specification of rolling mill

Parameter	Dimension
Roller surface roughness	0.36 $\mu$ m
Roller diameter	228.6 mm
Rolling speed	(22 rpm) or (2.303 rad/s) or (0.525 m/s)
Electric drive output	33 kW
Electric drive voltage	380 V



**Fig 3.3 : Cold rolling mill**

[Photo Courtesy: Thapar University campus, Patiala]

### 3.5 Test matrix

Design of experiments is foremost need in order to proceed for experiments. Three factors viz. lubrication, number of passes and roller gaps are focused on this study with various levels and experiments are performed according to the test matrix so that the impact of each and every factor and its level can be observed and analysed for the process. The following table (Table 3.6) shows the parameters variation for rolling of AA-6101 and mild steel.

Three conditions of lubrications were selected for comparison between two different type of lubricants used and also without lubrication. As water is added to water based lubricant i.e. Servosteerol C4 hence its viscosity somehow reduces, so that effect of viscosity can also be visualized.

**Table 3.7:** Factors and their levels for cold rolling process

Factors	Levels		
	Level 1	Level 2	Level 3
Lubricant	No lubrication	Servorol light	Servosteerol C 4
No. of passes	5	10	15
Roller gap	3 mm	2.4 mm	1.8 mm

**Table 3.8:** Design of experiment for cold rolling process

<b>Experiment No.</b>	<b>Lubricant</b>	<b>No. of passes</b>	<b>Roll gap (mm)</b>
1	No lubrication	5	3.0
2	No lubrication	5	2.4
3	No lubrication	5	1.8
4	No lubrication	10	3.0
5	No lubrication	10	2.4
6	No lubrication	10	1.8
7	No lubrication	15	3.0
8	No lubrication	15	2.4
9	No lubrication	15	1.8
10	Servorol light	5	3.0
11	Servorol light	5	2.4
12	Servorol light	5	1.8
13	Servorol light	10	3.0
14	Servorol light	10	2.4
15	Servorol light	10	1.8
16	Servorol light	15	3.0
17	Servorol light	15	2.4
18	Servorol light	15	1.8
19	Servosteerol C 4	5	3.0
20	Servosteerol C 4	5	2.4
21	Servosteerol C 4	5	1.8
22	Servosteerol C 4	10	3.0
23	Servosteerol C 4	10	2.4
24	Servosteerol C 4	10	1.8
25	Servosteerol C 4	15	3.0
26	Servosteerol C 4	15	2.4
27	Servosteerol C 4	15	1.8

The above factors and their levels were estimated from pilot studies. Pilot study has shown that if there is decrease in number of passes from five it will lead to very small change in thickness, minor influence on the flattening of surface roughness. So, to investigate the effect of surface smoothing and characterize the effect transfer layers ranges of number of passes and rollers gaps are set accordingly.

Given below tables depicting the test matrix for experiments conducted by adding nano-clay particles in the mineral based lubricant and water based lubricant. These experiments were conducted in order to analyse the effect of nanoparticles on the surface features of rolled strips.

**Table 3.9:** Factors and their levels for cold rolling process done by adding nano-clay particles in lubricants

Factors	Levels	
	Level 1	Level 2
% of clay in lubricant	1%	2%
No. of passes	5	10
Roller gap	3.0 mm	2.4 mm

**Table 3.10:** Design of experiment for cold rolling process done by adding nano-clay particles in Servorol light, mineral based lubricant

Experiment No.	% of clay	No. of passes	Roll gap
1	1	5	3.0
2	1	5	2.4
3	1	10	3.0
4	1	10	2.4
5	2	5	3.0
6	2	5	2.4
7	2	10	3.0
8	2	10	2.4

**Table 3.11:** Design of experiment for cold rolling process done by adding nano-clay particles in Servosteerol C4, water based lubricant

Experiment No.	% of clay	No. of passes	Roll gap
1	1	5	3.0
2	1	5	2.4
3	1	10	3.0
4	1	10	2.4
5	2	5	3.0
6	2	5	2.4
7	2	10	3.0
8	2	10	2.4

### 3.6 Sample preparation for cold rolling

To perform the experiments, aluminium alloy (AA-6101) and mild steel sheets with dimensions 380×75×6 mm were taken. The sheets were cold rolled to plastic deformation on the two-high reversing rolling machine.

54 Samples of both AA-6101 and mild steel i.e. 27 samples of each respectively were cut from the stock plate of 4572×75×6 mm using power press machine. Before proceeding for cold rolling the surface roughness, micro hardness, surface morphology and micro structures of the base materials were investigated.



**Fig 3.4 :** Cold rolling sample

[Photo Courtesy: Thapar University campus, Patiala]

Samples were cleaned by using acetone, so as to remove the dirt particles and various impurities, including removal of residual lubricants, if any. After sample preparations the samples of both AA-6101 and mild steel were cold rolled according to experiments mentioned in Table 3.7. Lubricating oil was applied using sponge piece so that lubricant should evenly and

properly applied on sample sheet. The rolls and samples were degreased with alcohol and acetone before every pass.

After performing the experiments the samples were immediately cleaned, degreased, de-scaled so as to get proper results. AA-6101 samples were cleaned and degreased using acetone. De-scaling of mild steel is done using copper brush because it is softer than mild steel and it will not scratch the mild steel sheet. The samples were cut parallel to the original direction of rolling. Following steps were followed to perform the experiments involving cold rolling:

1. 27 samples of dimension  $380 \times 7 \times 56$  each from AA-6101 and Mild Steel stock were cut and cleaned with acetone.
2. Rollers of rolling mills were also cleaned before experiments.
3. Dry rolling for both AA-6101 and Mild Steel samples was performed.
4. Rollers were again cleaned using acetone.
5. Preparation of lubricating oil was done. For water based lubricant the ratio of oil in water used for experiments is 1:2 i.e. one part of oil and two part of water by volume.
6. Lubricating oil was applied on each and every sample before rolling with sponge piece and also after every 3 passes lubricant is applied on sample so as to achieve the full impact of lubrication.
7. Samples of appropriate dimensions were cut from cold rolled stock for various testing.

In addition to above, experiment procedure for cold rolling done by adding nano-clay particles in lubricant are performed in the following manners.

- 1) 16 samples of dimension  $380 \times 7 \times 56$  each from AA-6101 and Mild Steel stock were cut and cleaned with acetone.
- 2) Rollers of rolling mills were also cleaned before experiments.
- 3) Preparation of lubricating oil was done. 1% nano clay particles and 2% nano clay particles were added in each 200 ml of lubricating oil. After adding clay the solution was made homogeneous with the help of magnetic stirrer.
- 4) Lubricating oil was applied on each and every sample before rolling with sponge piece and also after every 3 passes lubricant is applied on sample so as to achieve the full impact of lubrication.
- 5) Samples of appropriate dimensions were cut from cold rolled stock for various testings.

### 3.7 Testing of rolled specimens

After cold rolling, various tests were performed so as to observe and study the post effects of cold rolling. Different types of samples were prepared to perform different types of characterizations. Following sections describes the various tests or characterizations that were performed in this study.

#### 3.7.1 Surface roughness measurement

Surface roughness has impact on several useful characteristics, such as friction, wear and tear, capability of spreading and application of a lubricant etc. Therefore, the examination of surface roughness of work piece is extremely vital to evaluate the superiority of the processed components. The valuation of surface roughness of cold rolled samples was done using a direct contact method type surface roughness analyser. The roughness analyser used here is Mitutoyo SJ-400. It is a contact type roughness analyser.

Rolled sample is cleaned properly with acetone and surface roughness is calculated using the above mentioned analyser. Surface roughness of mild steel sample was done after de-scaling. Average roughness ( $R_a$ ) for three measurements for each tabulated reading were taken to improve the accuracy of the acquired data.



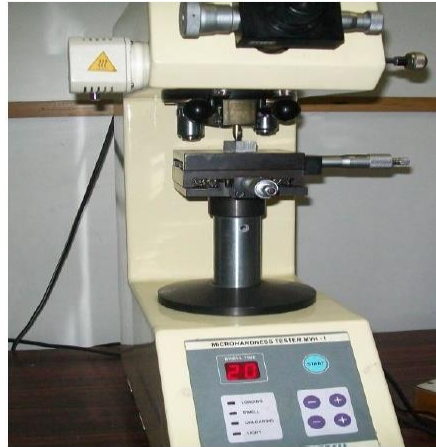
**Fig 3.5** : Surface roughness tester

[Photo Courtesy: Thapar University campus, Patiala]

#### 3.7.2 Micro hardness

Micro hardness testing machine was used for determining the hardness of a material on a microscopic level. The hardness test is a simple, easy and non-destructive method which is an important and widely used test for the purpose of quickly quantifying or evaluating the

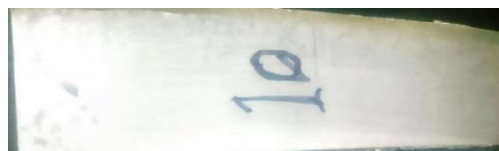
mechanical properties A diamond indenter is indented into the material by loads from few grams to 1Kg. The indenter (made of diamond) has a square-base pyramidal geometry with an included angle of  $136^\circ$ . As per ASTM standards 200 gm of constant load was applied on AA-6101 samples. The indenter mark length, calculated microscopically, and the test load are used to compute a hardness value.



**Fig 3.6:** Micro hardness tester

[Photo Courtesy: Thapar University campus, Patiala]

Specimen preparation for micro indentation hardness testing is not a minor issue because it requires metallographic finishing. Sample was cut from the base and rolled stock and polished up to metallographic finish. At least five indents were made across the polished surface of a fully machined test specimen and the result is reported as the average value.



**Fig 3.7 :** Micro hardness testing sample

[Photo Courtesy: Thapar University campus, Patiala]

### 3.7.3 Surface morphology

Surface morphology study is done on the basis of images obtained from the optical and electron microscope. This was done with the help of Lieca's metallurgical microscope and SEM (Scanning Electron Microscopy). Lieca's metallurgical microscope is used to acquire the optical images of the surface at high magnification. Due to variation in refractive indices there appear

different grey or color shades on the surface. Sample preparation involves only cleaning of surfaces with acetone and immediately visualized.



**Fig 3.8 :** Metallurgical microscope

[Photo Courtesy: Thapar University campus, Patiala]

The scanning electron microscopy (SEM) is used for observation of specimen surfaces. When the specimen is irradiated with a fine electron beam (called an electron probe), secondary electrons are emitted from the specimen surface. Topography of the surface can be observed by the two-dimensional scanning of the electron probe over the surface and acquisition of an image from the detected secondary electrons. SEM analysis is a “non-destructive” test because the fine electron beam doesn’t leads to the loss in the volume from the work piece surface. It is a high performance and low vacuum SEM for fast characterization and imaging of fine structures and has a magnification range 5–300,000 X. The selectable “low vacuum” mode allows for observation of specimens that cannot be viewed at high vacuum due to excessive water content (like many biological samples) or because they have a non-conductive surface (Raturi, 2014). JEOL JSM-6510LV will be used to study the morphology of the rolled strip whose specifications are given below:

**Table 3.12:** Specification of JEOL JSM-6510LV

[[http://www.jeolusa.com/PRODUCTS/ScanningElectronMicroscopes\(SEM\)/HVLVTungstenLaB6SEMs/JSM-6510LV/tabid/553/Default.aspx#222269-specifications](http://www.jeolusa.com/PRODUCTS/ScanningElectronMicroscopes(SEM)/HVLVTungstenLaB6SEMs/JSM-6510LV/tabid/553/Default.aspx#222269-specifications)]

<b>Resolution</b>	High Vacuum mode: 3.0 nm (30kV), 8nm (3kV), 15nm (1kV) Low Vacuum mode: 4.0 nm (30kV)
<b>Accelerating voltage</b>	500V to 30 kV

<b>Magnification</b>	x5 to 300,000 (printed as a 128mm x 96mm micrograph)
<b>LV Detector</b>	Multi-segment BSED (std.) LV-SED (option)
<b>LV Pressure</b>	10 to 270 Pa
<b>Resolution</b>	High Vacuum mode: 3.0 nm (30kV), 8nm (3kV), 15nm (1kV) Low Vacuum mode: 4.0 nm (30kV)



**Fig 3.9 :** Scanning Electron Microscope  
[Photo Courtesy: Thapar University campus, Patiala]

# Chapter 4

## Results and Discussion

### 4.1 Introduction

This chapter deals with the detailed discussion on the results obtained from the experimental work involving cold rolling parameters such as thickness reduction and roller gaps as well as surface features of rolled strips such as surface roughness, micro hardness, morphological micrographs, etc are carried out.

### 4.2 Thickness reduction analysis

In longitudinal cold rolling of sheet the volume of sheet remains constant, since no material removal takes place and there is no change in the plastic volume during plastic deformation of sheet, [Ginzbug *et al.*, 1991].

**Table 4.1:** Dimensional results of cold rolled AA-6101 sheets

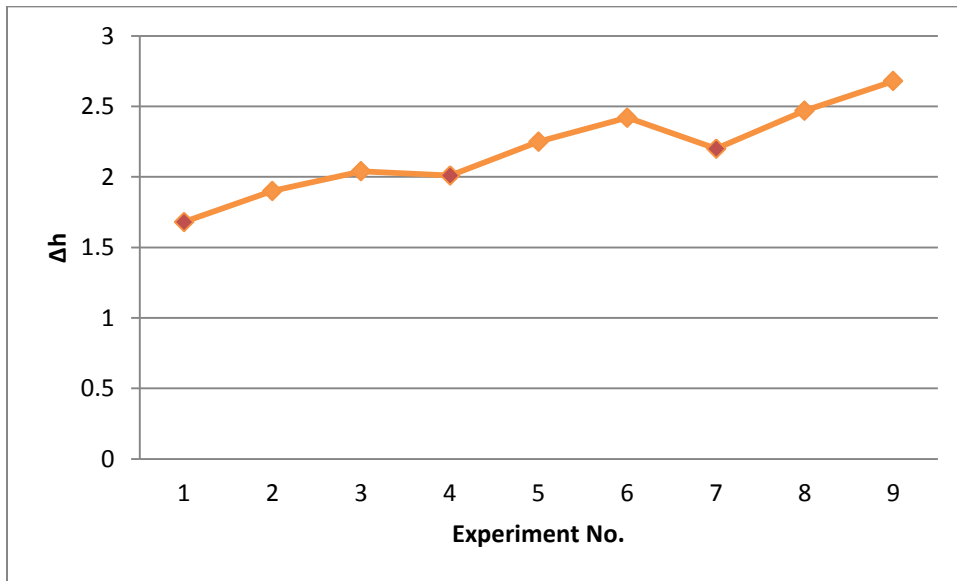
Exp. No.	Lubricant	No. of passes	Roll gap (mm)	Initial Length (L <sub>1</sub> ) (mm)	Initial Thickness (T <sub>1</sub> ) (mm)	Final Length (L <sub>2</sub> ) (mm)	Final Thickness (T <sub>2</sub> ) (mm)	L <sub>1</sub> × T <sub>1</sub> (mm) <sup>2</sup>	L <sub>2</sub> × T <sub>2</sub> (mm) <sup>2</sup>	Δh = T <sub>1</sub> - T <sub>2</sub> (mm)
1	No lubrication	5	3.0	380	6	498	4.32	2280	2151.36	1.68
2	No lubrication	5	2.4	380	6	524	4.10	2280	2148.40	1.90
3	No lubrication	5	1.8	380	6	570	3.96	2280	2257.20	2.04
4	No lubrication	10	3.0	380	6	564	3.99	2280	2250.36	2.01
5	No lubrication	10	2.4	380	6	600	3.75	2280	2250.00	2.25
6	No lubrication	10	1.8	380	6	632	3.58	2280	2262.56	2.42
7	No lubrication	15	3.0	380	6	597	3.80	2280	2268.60	2.20
8	No lubrication	15	2.4	380	6	640	3.53	2280	2259.20	2.47

9	No lubrication	15	1.8	380	6	680	3.32	2280	2257.60	2.68
10	Servorol light	5	3.0	380	6	444	4.97	2280	2206.68	1.03
11	Servorol light	5	2.4	380	6	487	4.51	2280	2196.37	1.49
12	Servorol light	5	1.8	380	6	502	4.00	2280	2008.00	1.99
13	Servorol light	10	3.0	380	6	456	4.81	2280	2193.36	1.19
14	Servorol light	10	2.4	380	6	498	4.32	2280	2151.36	1.68
15	Servorol light	10	1.8	380	6	593	3.70	2280	2194.10	2.30
16	Servorol light	15	3.0	380	6	490	4.40	2280	2156.00	1.60
17	Servorol light	15	2.4	380	6	618	3.67	2280	2268.06	2.33
18	Servorol light	15	1.8	380	6	650	3.48	2280	2262.00	2.52
19	Servosteerol C 4	5	3.0	380	6	469	4.50	2280	2110.50	1.50
20	Servosteerol C 4	5	2.4	380	6	499	4.36	2280	2175.64	1.64
21	Servosteerol C 4	5	1.8	380	6	548	4.00	2280	2192.00	2.00
22	Servosteerol C 4	10	3.0	380	6	567	3.98	2280	2256.66	2.02
23	Servosteerol C 4	10	2.4	380	6	591	3.80	2280	2245.80	2.20
24	Servosteerol C 4	10	1.8	380	6	600	3.61	2280	2166.00	2.39
25	Servosteerol C 4	15	3.0	380	6	548	4.06	2280	2224.88	1.94
26	Servosteerol C 4	15	2.4	380	6	602	3.63	2280	2185.26	2.37
27	Servosteerol C 4	15	1.8	380	6	695	3.25	2280	2258.75	2.75

As AA-6101 is soft and malleable metal so there is minor enlargement in the width dimension is observed because metal has spreads in both directions i.e. along length and

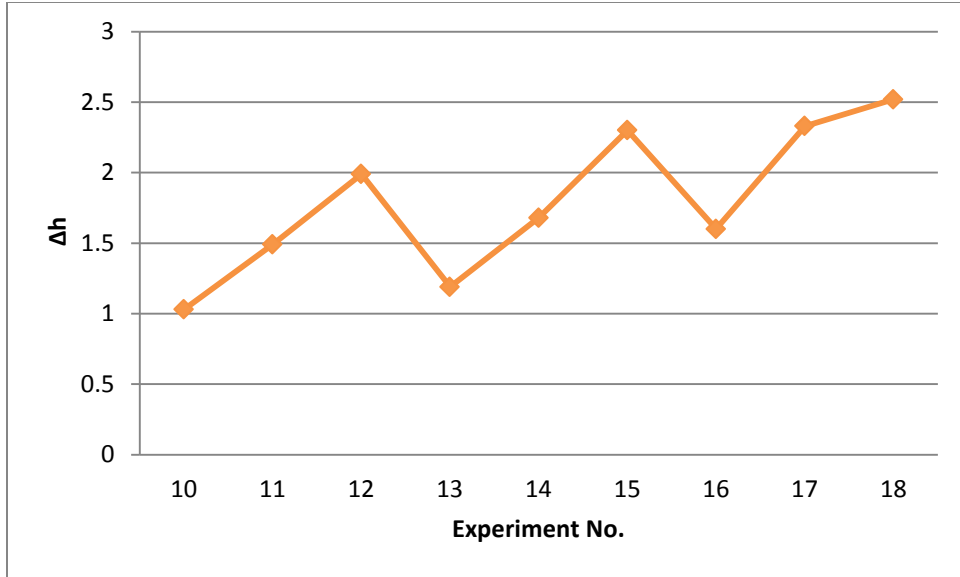
along width because both longitudinal as well as transverse loads act during cold rolling but the value of longitudinal load is more dominating than the load acting along transverse direction. So, practically it has been analysed that  $\text{length} \times \text{thickness (initial)} > \text{length} \times \text{thickness (final)}$ . It implies that there is increase width of the sheet also with increase in the length. In cold rolling process, the plastic deformation results reduction in thickness and also reason for increase in width of sheet, this is called spreading.

$$\Delta h \text{ (draft)} = \text{Initial thickness} - \text{final thickness}$$



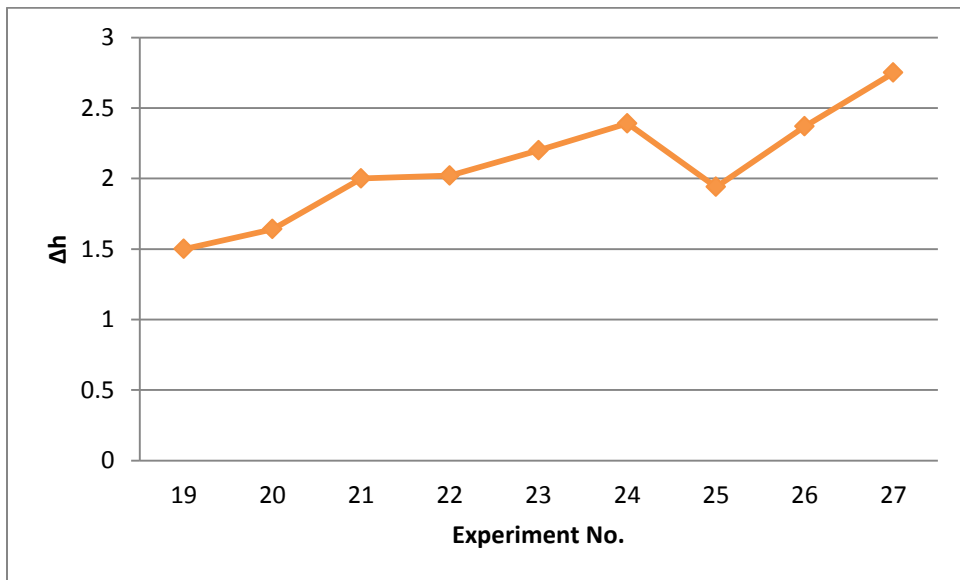
**Fig 4.1:** Variation of  $\Delta h$  w.r.t rolling parameter for dry rolling for AA-6101

Fig. 4.1 shows the variation of draft with number of passes and roller gaps. It is very much clear from the above graphical data that draft increases with decrease in roller gap and increase in number of passes. There was no lubrication used for these experiments.



**Fig 4.2:** Variation of  $\Delta h$  w.r.t rolling parameter for rolling done using mineral based oil AA-6101

It is also very much clear from the above graphical data that draft increases with decrease in roller gap and increase in number of passes. But as compared to dry condition rolling, value for draft in this case is less due to use of lubricant which reduces the coefficient of friction. Due to which rolling takes place with less rolling force. In this way, the smooth transition of thickness reduction can be achieved by the use of lubricant.



**Fig 4.3:** Variation of  $\Delta h$  w.r.t rolling parameter for rolling done using water based oil AA-6101

The above plot shows the similar behavior as compared to the rolling done without lubrication, but there is change in values due to the use of less viscous lubricating oil. As these experiments were performed using Servosteerol C4 which is a water based lubricant and less viscous than mineral based oil i.e. Servorol light. Hence coefficient of friction for these experiments would lie in between the coefficient of friction for dry rolling and rolling done using mineral oil.

**Table 4.2:** Dimensional results of cold rolled Mild Steel sheets

Exp No.	Lubricant	No. of passes	Roll gap (mm)	Initial Length ( $L_1$ ) (mm)	Initial Thickness ( $T_1$ ) (mm)	Final Length ( $L_2$ ) (mm)	Final Thickness ( $T_2$ ) (mm)	$L_1 \times T_1$ (mm) <sup>2</sup>	$L_2 \times T_2$ (mm) <sup>2</sup>	$\Delta h = T_1 - T_2$ (mm)
1	No lubrication	5	3.0	380	6	426	5.31	2280	2262.06	0.69
2	No lubrication	5	2.4	380	6	433	5.19	2280	2247.27	0.81
3	No lubrication	5	1.8	380	6	453	5.01	2280	2269.53	0.99
4	No lubrication	10	3.0	380	6	427	5.26	2280	2246.02	0.74
5	No lubrication	10	2.4	380	6	445	5.11	2280	2273.95	0.89
6	No lubrication	10	1.8	380	6	462	4.89	2280	2259.18	1.11
7	No lubrication	15	3.0	380	6	446	5.09	2280	2270.14	0.91
8	No lubrication	15	2.4	380	6	464	4.91	2280	2278.24	1.09
9	No lubrication	15	1.8	380	6	487	4.68	2280	2279.16	1.32
10	Servorol light	5	3.0	380	6	412	5.44	2280	2241.28	0.56
11	Servorol light	5	2.4	380	6	430	5.23	2280	2248.90	0.77
12	Servorol light	5	1.8	380	6	444	5.1	2280	2264.40	0.90
13	Servorol light	10	3.0	380	6	426	5.3	2280	2257.80	0.70
14	Servorol light	10	2.4	380	6	437	5.17	2280	2259.29	0.83

15	Servorol light	10	1.8	380	6	451	5.04	2280	2273.04	0.99
16	Servorol light	15	3.0	380	6	440	5.14	2280	2261.60	0.86
17	Servorol light	15	2.4	380	6	450	5	2280	2250.00	1.00
18	Servorol light	15	1.8	380	6	473	4.76	2280	2251.48	1.24
19	Servosteerol C 4	5	3.0	380	6	421	5.36	2280	2256.56	0.64
20	Servosteerol C 4	5	2.4	380	6	433	5.22	2280	2260.26	0.75
21	Servosteerol C 4	5	1.8	380	6	447	5.06	2280	2261.82	0.94
22	Servosteerol C 4	10	3.0	380	6	431	5.27	2280	2271.37	0.73
23	Servosteerol C 4	10	2.4	380	6	440	5.14	2280	2261.60	0.86
24	Servosteerol C 4	10	1.8	380	6	460	4.93	2280	2267.80	1.07
25	Servosteerol C 4	15	3.0	380	6	441	5.12	2280	2257.92	0.88
26	Servosteerol C 4	15	2.4	380	6	456	4.94	2280	2252.64	1.06
27	Servosteerol C 4	15	1.8	380	6	483	4.71	2280	2274.93	1.26

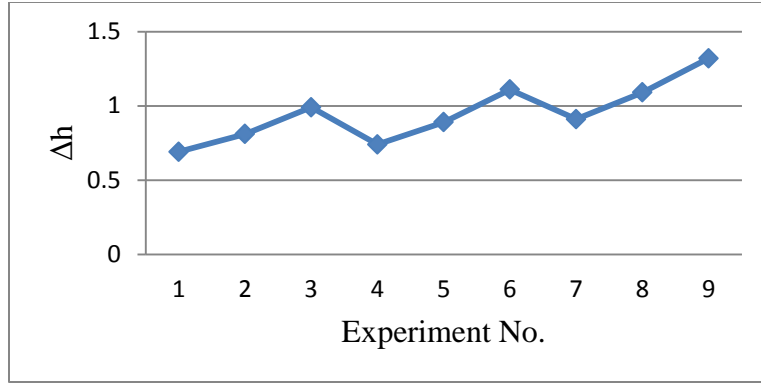
As mild steel is harder than AA-6101 and there is very small change in the final length and final thickness of the mild steel sheet this is because more sturdy, powerful, high velocity mill is required. Mild steel was taken into account so as to take a referral material for roughness formulation and calculation which has been explained in next article.

In case of mild steel sheets, it is has been analysed that

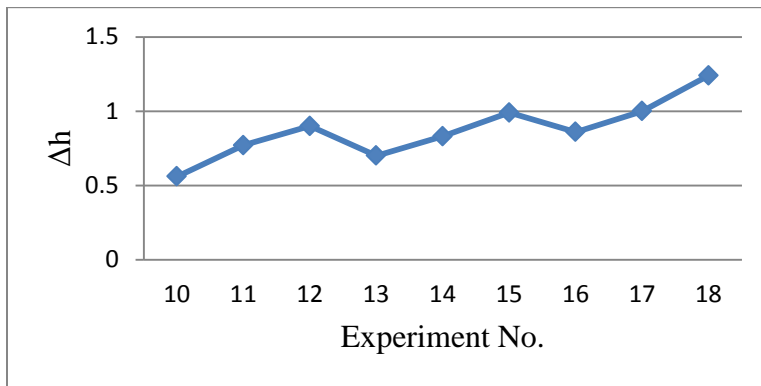
$$\text{length} \times \text{thickness (initial)} \simeq \text{length} \times \text{thickness (final)}$$

Also very less spreading phenomenon take place in case of mild steel sheets.

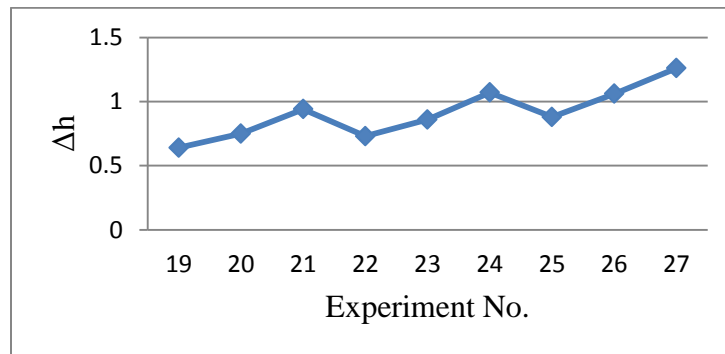
$$\Delta h (\text{draft}) = \text{Initial thickness} - \text{final thickness}$$



**Fig 4.4:** Variation of  $\Delta h$  w.r.t rolling parameter for dry rolling for mild steel



**Fig 4.5:** Variation of  $\Delta h$  w.r.t rolling parameter for rolling done using mineral oil for mild steel



**Fig 4.6:** Variation of  $\Delta h$  w.r.t rolling parameter for rolling done using water based oil for mild steel

In case of mild steel it is observed that there is very minor change in the value of draft due to use of lubricants, although the curve follows the similar trend. This is because rolling force is not capable for higher reductions for hard metals. However, it can be used for the modification of the

surface features of the work materials. Following section will provide the clearer picture on the effect of this decrease in rolling force in enhancement of surface roughness.

### 4.3 Surface Roughness Study

Surface roughness values were obtained using contact type roughness tester. Three values of  $R_a$  were taken at three different positions and their average is calculated. These values were then compared with the theoretical values obtained by using linear regression formula for surface roughness values obtained through cold rolling. The linear regression model explains that the response Y depends on the input variables and a random error that represent for missing variables and measurement error. Linear implies to the fact that the response Y is a linear combination of the unidentified parameters. In order to accomplish this, the regression model must be fitted to previously observed values. Multiple regression is often necessary even when the investigator is only interested in the effects of one of the independent variables. [Sykes , 1986]. For theoretical validation of results mild steel is taken as reference parameter, [Valíček *et al.*, 2014].

Given below table provides the experimental values of surface roughness of AA-6101 and Mild steel. The effect of lubrication, roller gap, number of passes and even the effect of draft value is also analysed. Befor rolling the surafe roughness value i.e  $R_a$  is 1.49  $\mu\text{m}$ .

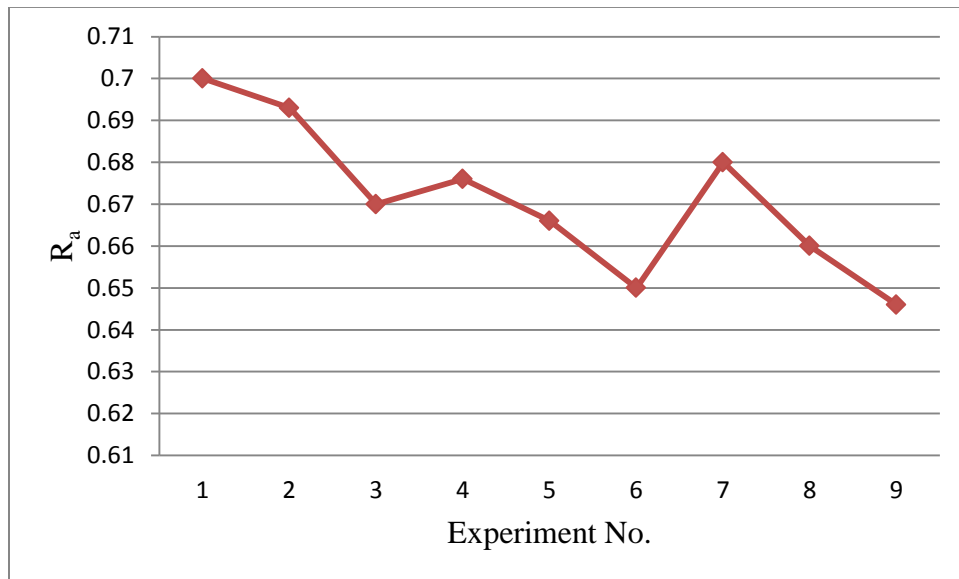
**Table 4.3:** Surface roughness values for AA-6101

Exp. No.	Lubricant	No. of passes	Roll gap (mm)	$\Delta h$	$R_a$ (1)	$R_a$ (2)	$R_a$ (3)	Average $R_a$ ( $\mu\text{m}$ )
1	No lubrication	5	3.0	1.68	0.69	0.71	0.70	0.70
2	No lubrication	5	2.4	1.90	0.71	0.69	0.68	0.69
3	No lubrication	5	1.8	2.04	0.66	0.68	0.69	0.67
4	No lubrication	10	3.0	2.01	0.67	0.69	0.65	0.67

5	No lubrication	10	2.4	2.25	0.65	0.67	0.68	0.66
6	No lubrication	10	1.8	2.42	0.63	0.66	0.65	0.64
7	No lubrication	15	3.0	2.20	0.69	0.67	0.68	0.68
8	No lubrication	15	2.4	2.47	0.67	0.64	0.67	0.66
9	No lubrication	15	1.8	2.68	0.65	0.64	0.66	0.65
10	Servorol light	5	3.0	1.03	0.70	0.71	0.69	0.70
11	Servorol light	5	2.4	1.49	0.66	0.64	0.68	0.64
12	Servorol light	5	1.8	1.99	0.63	0.65	0.65	0.64
13	Servorol light	10	3.0	1.19	0.64	0.66	0.64	0.64
14	Servorol light	10	2.4	1.68	0.62	0.59	0.58	0.60
15	Servorol light	10	1.8	2.30	0.59	0.60	0.57	0.59
16	Servorol light	15	3.0	1.60	0.60	0.58	0.62	0.60
17	Servorol light	15	2.4	2.33	0.58	0.57	0.59	0.58
18	Servorol light	15	1.8	2.52	0.55	0.53	0.56	0.55
19	Servosteerol C 4	5	3.0	1.50	0.68	0.72	0.70	0.70

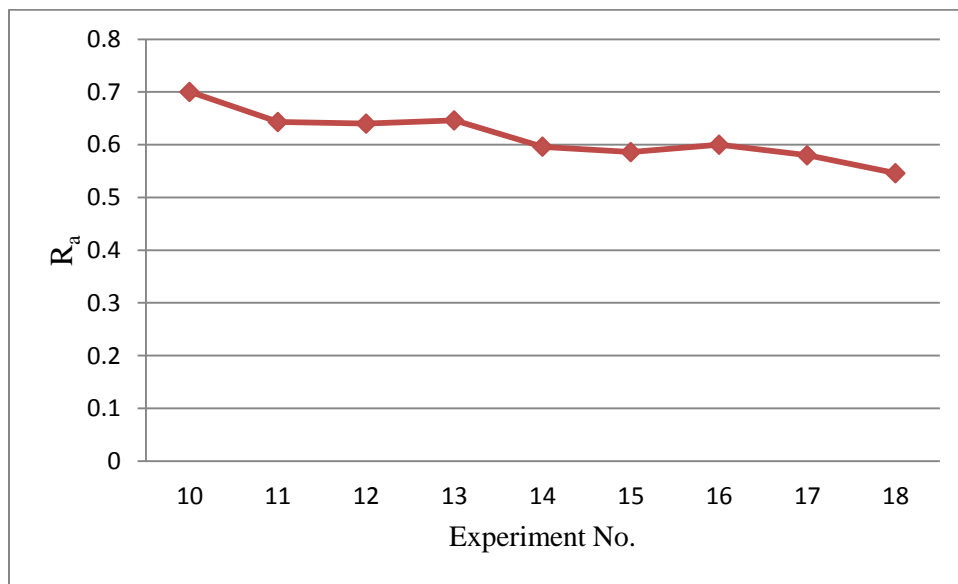
20	Servosteerol C 4	5	2.4	1.64	0.67	0.68	0.66	0.67
21	Servosteerol C 4	5	1.8	2.00	0.66	0.64	0.69	0.66
22	Servosteerol C 4	10	3.0	2.02	0.65	0.63	0.67	0.65
23	Servosteerol C 4	10	2.4	2.20	0.62	0.65	0.63	0.63
24	Servosteerol C 4	10	1.8	2.39	0.63	0.62	0.61	0.62
25	Servosteerol C 4	15	3.0	1.94	0.62	0.66	0.64	0.64
26	Servosteerol C 4	15	2.4	2.37	0.59	0.61	0.60	0.60
27	Servosteerol C 4	15	1.8	2.75	0.57	0.60	0.63	0.60

From the above data following plot (Fig 4.7) can be constructed to show the variation of  $R_a$  w.r.t rolling parameter for rolling done in dry conditions for AA-6101.



**Fig 4.7:** Variation of  $R_a$  w.r.t rolling parameter for rolling done in dry conditions for AA-6101

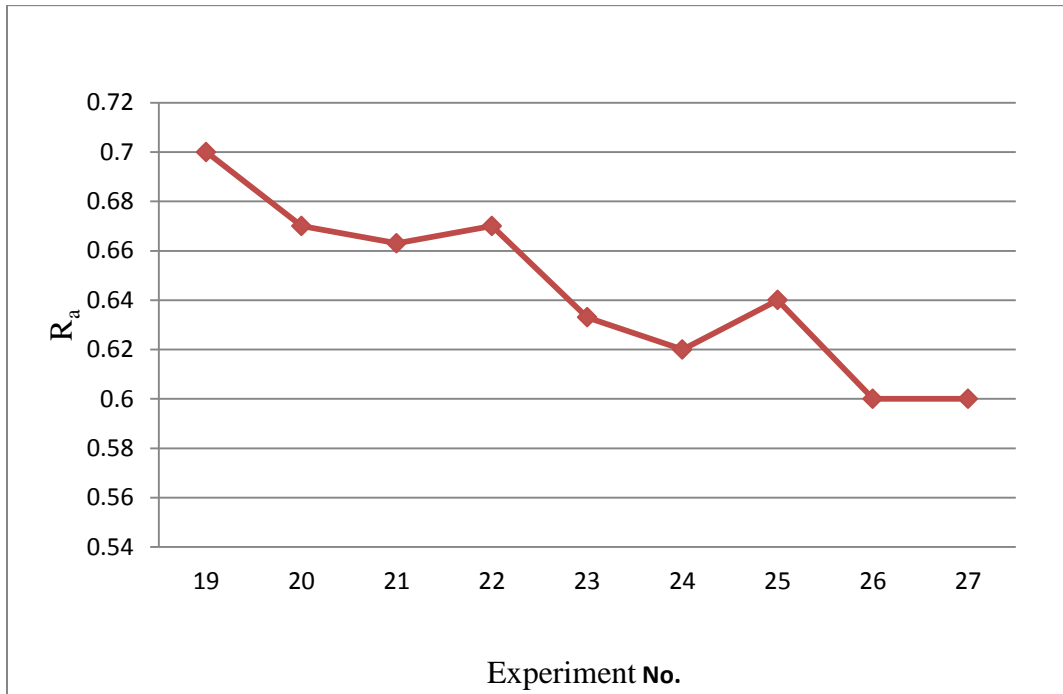
Referring to Fig 4.7 it is very much clear that surface roughness value decreases with increase in no. of passes and decrease in roller gap or increase in draft value. From graphical view it has been observed that for experiment number 1, 2, 3 the  $R_a$  value decreases because for these experiments the roller gap keeps on decreasing but number of passes i.e. 5 remains same. For experiment number 4,5,6 the roller gap is same as for experiment number 1,2,3 respectively but number of passes increased to 10 and further same conditions are applicable for experiment number 7,8,9 but number of passes increases to 15. From this it can be said that the smoother surface is obtained by decreasing roller gap and increase in number of passes.



**Fig 4.8:** Variation of  $R_a$  w.r.t rolling parameter for rolling done using mineral oil for AA-6101

From the above figure (Fig 4.8) it is very much clear that surface roughness value decreases with increase in number of passes and decrease in roller gap which further these parameters leads to increase in draft value. Referring to the above figure it has been observed that for experiment number 10, 11, 12 the  $R_a$  value decreases because for these experiments the roller gap keeps on decreasing but number of passes i.e. 5 remains same. For experiment number 13, 14, 15 the roller gap is same as for experiment number 10, 11,12 respectively but number of passes increased to 10 and further same conditions are applicable for experiment number 16,17,18 but number of passes increases to 15. From this it can be said that the smoother surface is obtained by decreasing roller gap and increase in number of passes.

As this rolling was done using Servorol light as lubricant and if comparison in results is done with dry condition rolling then it proves that surface quality is improved using this lubricant. The main reason is that the presence of lubrication into the contact prevents the asperity indentation into the rolled materials and rather it acts as the flattening of the surface asperities by the fluid pressure which leads to decrease the surface roughness and hence smooth surface is obtained.



**Fig 4.9:** Variation of  $R_a$  w.r.t rolling parameter for rolling done using water based oil for AA-6101

Conditions for experiment number 19 to 27 are same as that for experiment number 1 to 9 and 10 to 18. The only difference is that experiment number 1 to 9 were conducted without lubrication and experiment number 10 to 18 were conducted using Servorol light lubricant which is mineral based lubricant and experiment number 19 to 27 were conducted using Servosteerol C4 which is water based lubricant.

Servorol light is more viscous and dense as compare to Servosteerol C4 that is why less roughness values were obtained using Servorol light as compare to dry rolling and rolling done using Servosteerol C4. [Lenard *et al.*, 2004] verified that that large the viscosity of oil a lesser amount of is the surface roughness. Befor rolling the surafe roughness value i.e  $R_a$  of mild steel is  $1.29 \mu\text{m}$ .

**Table 4.4:** Surface roughness values for Mild Steel

<b>Exp. No.</b>	<b>Lubricant</b>	<b>No. of passes</b>	<b>Roll gap (mm)</b>	<b><math>\Delta h</math></b>	<b><math>R_a</math> (1)</b>	<b><math>R_a</math> (2)</b>	<b><math>R_a</math> (3)</b>	<b>Average <math>R_a</math> (<math>\mu m</math>)</b>
1	No lubrication	5	3.0	0.69	0.80	0.78	0.79	0.79
2	No lubrication	5	2.4	0.81	0.79	0.77	0.75	0.77
3	No lubrication	5	1.8	0.99	0.76	0.76	0.77	0.77
4	No lubrication	10	3.0	0.74	0.77	0.77	0.75	0.76
5	No lubrication	10	2.4	0.89	0.74	0.78	0.76	0.76
6	No lubrication	10	1.8	1.11	0.75	0.76	0.79	0.77
7	No lubrication	15	3.0	0.91	0.73	0.77	0.75	0.75
8	No lubrication	15	2.4	1.09	0.75	0.76	0.79	0.77
9	No lubrication	15	1.8	1.32	0.77	0.75	0.73	0.75
10	Servorol light	5	3.0	0.56	0.78	0.79	0.81	0.79
11	Servorol light	5	2.4	0.77	0.75	0.77	0.79	0.77
12	Servorol light	5	1.8	0.90	0.79	0.78	0.81	0.79
13	Servorol light	10	3.0	0.70	0.78	0.76	0.79	0.78
14	Servorol light	10	2.4	0.83	0.76	0.77	0.78	0.77
15	Servorol light	10	1.8	0.99	0.74	0.70	0.72	0.72
16	Servorol light	15	3.0	0.86	0.79	0.80	0.81	0.80
17	Servorol light	15	2.4	1.00	0.74	0.75	0.76	0.75
18	Servorol light	15	1.8	1.24	0.76	0.78	0.74	0.76
19	Servosteerol C 4	5	3.0	0.64	0.77	0.79	0.78	0.78
20	Servosteerol C 4	5	2.4	0.75	0.79	0.75	0.77	0.77
21	Servosteerol C 4	5	1.8	0.94	0.76	0.77	0.78	0.77
22	Servosteerol C 4	10	3.0	0.73	0.78	0.74	0.76	0.76
23	Servosteerol C 4	10	2.4	0.86	0.79	0.81	0.79	0.80
24	Servosteerol C 4	10	1.8	1.07	0.80	0.78	0.74	0.77
25	Servosteerol C 4	15	3.0	0.88	0.82	0.80	0.81	0.81
26	Servosteerol C 4	15	2.4	1.06	0.76	0.79	0.82	0.79
27	Servosteerol C 4	15	1.8	1.26	0.73	0.78	0.74	0.75

### 4.3.1 Surface roughness model

Validation of results obtained was validated by carefully selected roughness model. [Valíček *et al.*,2014] explained the relation for estimation of surface roughness value ( $R_a$ ) for cold rolling. The main reason for selecting this relation is the similarity of the rolling parameters and conditions. Following algorithm was followed theoretical modeling of relation.

$$K_P = \frac{10^{12}}{E^2} \dots\dots\dots (1)$$

$K_P$  is the constant of plasticity

$E$  is the modulus of elasticity, it is selected as comparative parameter.

**Table 4.5:** Properties of rolling sheets

Metal sheet	Modulus Of Elasticity (E) (MPa)	Plasticity Constant ( $K_P$ )
AA-6101	$80 \times 10^3$	156.25
Mild Steel	$210 \times 10^3$	22.67

$K_P$  value for AA-6101 and Mild Steel is calculated using equation (1).

Values of modulus of elasticity was obtained from web, [[http://www.engineeringtoolbox.com/young-modulus-d\\_417.html](http://www.engineeringtoolbox.com/young-modulus-d_417.html)]

$K_P$  was calculated to use its value in index proportion ( $I_{K_P}$ ).

Index proportion is unique form of algebra equation. It is developed to build two ratios or formulate equivalent fractions.

$$I_{K_P} = \sqrt{\frac{K_{Pm.s}}{K_{PAA-6101}}} \dots\dots\dots (2)$$

This factor was applied in relation to surface roughness of individual materials in cold rolling.

$$I_{K_P} = 0.380$$

Mild steel is taken as reference parameter for following calculations.

The relation for  $R_a$  was established using  $K_P$ ,  $I_{K_P}$ ,  $\Delta h$ .

[Valíček *et al.*, 2014] obtained the given below result.

$$R_a(Theory) = -0.21 \cdot \Delta h \cdot I_{K_P} + 0.85 \dots\dots\dots (3)$$

To determine the theoretical roughness values above roughness model and equation (3) is used in the present study.

$\Delta h$  = draft

$I_{Kp}$  = Index proportion

**Table 4.6:** Comparison of theoretical and actual surface roughness values for cold rolled AA-6101

Exp No.	Lubricant	No. of passes	Roll gap (mm)	$\Delta h$ (mm)	$R_a$ ( $\mu\text{m}$ ) (Theoretical)	$R_a$ ( $\mu\text{m}$ ) (Actual)
1	No lubrication	5	3.0	1.68	0.71	0.70
2	No lubrication	5	2.4	1.90	0.69	0.69
3	No lubrication	5	1.8	2.04	0.68	0.67
4	No lubrication	10	3.0	2.01	0.68	0.67
5	No lubrication	10	2.4	2.25	0.67	0.66
6	No lubrication	10	1.8	2.42	0.65	0.64
7	No lubrication	15	3.0	2.20	0.67	0.68
8	No lubrication	15	2.4	2.47	0.65	0.66
9	No lubrication	15	1.8	2.68	0.63	0.65
10	Servorol light	5	3.0	1.03	0.76	0.70
11	Servorol light	5	2.4	1.49	0.73	0.64
12	Servorol light	5	1.8	1.99	0.69	0.64

13	Servorol light	10	3.0	1.19	0.75	0.65
14	Servorol light	10	2.4	1.68	0.71	0.59
15	Servorol light	10	1.8	2.30	0.66	0.58
16	Servorol light	15	3.0	1.60	0.72	0.60
17	Servorol light	15	2.4	2.33	0.66	0.58
18	Servorol light	15	1.8	2.52	0.64	0.54
19	Servosteerol C 4	5	3.0	1.50	0.73	0.70
20	Servosteerol C 4	5	2.4	1.64	0.71	0.67
21	Servosteerol C 4	5	1.8	2.00	0.69	0.66
22	Servosteerol C 4	10	3.0	2.02	0.68	0.65
23	Servosteerol C 4	10	2.4	2.20	0.67	0.63
24	Servosteerol C 4	10	1.8	2.39	0.66	0.62
25	Servosteerol C 4	15	3.0	1.94	0.69	0.64
26	Servosteerol C 4	15	2.4	2.37	0.66	0.60
27	Servosteerol C 4	15	1.8	2.75	0.63	0.60

From the above tabular data it is examined that the theoretical and calculated values are nearly same for experiment number 1 to 9. But for experiment number 10-27 the calculated

values of surface roughness is somehow less than that of theoretical values. This is due to the reason that the theoretical relation is only valid for dry rolling condition not for lubricated conditions. The improved surface was obtained because of lubrication.

So, there is a need of modification of the used model to incorporate the effect of lubrication. On careful observation of the data obtained, it is found that the roughness due to the presence of mineral oil is reduced to approximately 0.835 times of dry rolling case.

So, for experiment no. 10 to 18 if equation (3) is multiplied by 0.835 then new theoretical values of surface roughness will be approximately equal to the measured values of surface roughness.

Mathematically, from equation no. (3)

$$R_a (Theoretical) = -0.21 \cdot \Delta h \cdot I_{Kp} + 0.85$$

According to above mentioned statement,

$$R_a (New) = 0.835 R_a (Theoretical) \dots\dots\dots (4)$$

The above relation is valid only for rolling done with mineral oil.

**Table 4.7:** Result validation for cold rolled AA-6101

<b>Exp No.</b>	<b>R<sub>a</sub> (theoretical) (µm)</b>	<b>R<sub>a</sub> (measured) (µm)</b>	<b>R<sub>a</sub> (New) (µm)</b>
10	0.76	0.70	0.68
11	0.73	0.64	0.63
12	0.69	0.64	0.61
13	0.75	0.65	0.62
14	0.71	0.59	0.59
15	0.66	0.58	0.55
16	0.72	0.60	0.60
17	0.66	0.58	0.56
18	0.64	0.54	0.53

Similarly it has been observed from above Table 4.6 that for experiment no. 19 to 27 if equation (3) is multiplied with constant 0.952 then new theoretical values of surface roughness will be approximately equal to the measured values of surface roughness.

Mathematically, from equation (3)

$$R_a (Theoretical) = -0.21 \cdot \Delta h \cdot I_{Kp} + 0.85$$

According to above mentioned statement,

$$R_{a(New)} = 0.952 R_{a(Theoretical)} \dots\dots\dots (5)$$

The above relation is valid only for rolling done with water based oil.

**Table 4.8:** Result validation for cold rolled AA-6101

<b>Exp No.</b>	<b>R<sub>a</sub> (theoretical) (μm)</b>	<b>R<sub>a</sub> (measured) (μm)</b>	<b>R<sub>a</sub> (New) (μm)</b>
19	0.73	0.70	0.69
20	0.71	0.67	0.68
21	0.69	0.66	0.65
22	0.68	0.65	0.65
23	0.67	0.63	0.64
24	0.66	0.62	0.63
25	0.69	0.64	0.65
26	0.66	0.60	0.62
27	0.63	0.60	0.60

Thus, the influence coefficients in the existing model used here is modified to incorporate the influence of lubrication and material effect on the surface finish. Further refinement of the suggested model can be done by performing experiments involving different process and material parameter in presence of lubrication only.

**Table 4.9:** Comparison of theoretical and actual surface roughness values for cold rolled Mild Steel

<b>Exp No.</b>	<b>Lubricant</b>	<b>No. of passes</b>	<b>Roll gap (mm)</b>	<b>Δh (mm)</b>	<b>R<sub>a</sub> (μm) (Theoretical)</b>	<b>R<sub>a</sub> (μm) (Measured)</b>
1	No lubrication	5	3.0	1.68	0.79	0.79
2	No lubrication	5	2.4	1.90	0.78	0.78
3	No lubrication	5	1.8	2.04	0.77	0.77
4	No lubrication	10	3.0	2.01	0.79	0.77

5	No lubrication	10	2.4	2.25	0.77	0.76
6	No lubrication	10	1.8	2.42	0.76	0.77
7	No lubrication	15	3.0	2.20	0.77	0.75
8	No lubrication	15	2.4	2.47	0.76	0.77
9	No lubrication	15	1.8	2.68	0.74	0.75
10	Servorol light	5	3.0	1.03	0.80	0.79
11	Servorol light	5	2.4	1.49	0.78	0.77
12	Servorol light	5	1.8	1.99	0.77	0.79
13	Servorol light	10	3.0	1.19	0.79	0.78
14	Servorol light	10	2.4	1.68	0.78	0.77
15	Servorol light	10	1.8	2.30	0.77	0.72
16	Servorol light	15	3.0	1.60	0.78	0.80
17	Servorol light	15	2.4	2.33	0.77	0.75
18	Servorol light	15	1.8	2.52	0.75	0.76
19	Servosteerol C 4	5	3.0	1.50	0.79	0.78
20	Servosteerol C 4	5	2.4	1.64	0.78	0.77

21	Servosteerol C 4	5	1.8	2.00	0.77	0.77
22	Servosteerol C 4	10	3.0	2.02	0.79	0.76
23	Servosteerol C 4	10	2.4	2.20	0.78	0.80
24	Servosteerol C 4	10	1.8	2.39	0.76	0.77
25	Servosteerol C 4	15	3.0	1.94	0.77	0.81
26	Servosteerol C 4	15	2.4	2.37	0.76	0.79
27	Servosteerol C 4	15	1.8	2.75	0.74	0.75

From the above tabular data it is examined that the theoretical and calculated values are nearly same for experiment number 1 to 27. This is because either the selected lubricant is not effective for hard materials or the surface finish of hard material cold rolling is less effected by the presence of lubrication machine or lubricant is incapable. Also for this reason only mild steel is taken as reference parameter.

#### **4.3.2 Surface roughness study for rolling of sheets done adding nano-clay particles in lubricants.**

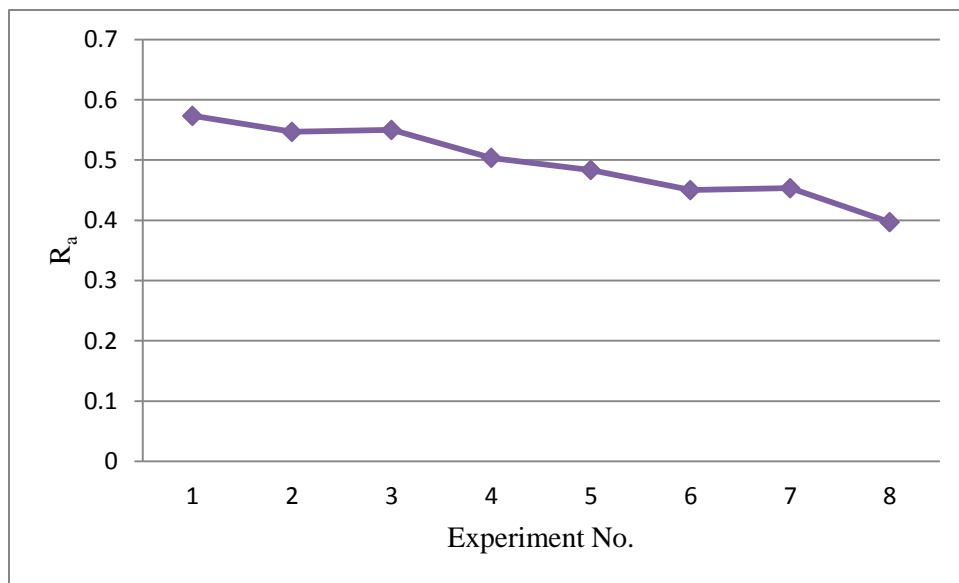
Given below table provides the experimental values of surface roughness of AA-6101 cold rolled by adding nano-clay particles in Servorol light lubricant. 1% and 2% of clay is added in oil, i.e. 2 gm of nano-clay added in 200 ml oil and 4 gm of nano-clay added in 200 ml of oil respectively.

**Table 4.10:** Surface roughness values For AA-6101 cold rolled by adding nano-clay particles in Servorol Light lubricant.

Exp. No.	% of clay	No. of passes	Roll gap (mm)	R <sub>a</sub> (1)	R <sub>a</sub> (2)	R <sub>a</sub> (3)	Average R <sub>a</sub> (µm)
1	1	5	3.0	0.58	0.53	0.61	0.57
2	1	5	2.4	0.55	0.54	0.55	0.54

3	1	10	3.0	0.52	0.55	0.58	0.55
4	1	10	2.4	0.49	0.5	0.52	0.50
5	2	5	3.0	0.49	0.47	0.49	0.48
6	2	5	2.4	0.48	0.43	0.44	0.45
7	2	10	3.0	0.43	0.45	0.48	0.45
8	2	10	2.4	0.37	0.42	0.4	0.39

It has been observed by increasing the clay content in mineral oil, the surface roughness significantly decreases. The above graphical and tabular data shows that nano clay particles play an important role in improving surface features. It helps in reducing coefficient of friction. In this section also no. of passes and roller gap plays a vital role. Increase in number of passes and decrease in roller gap lessens the roughness value by boundary or mixed lubrication mechanism.

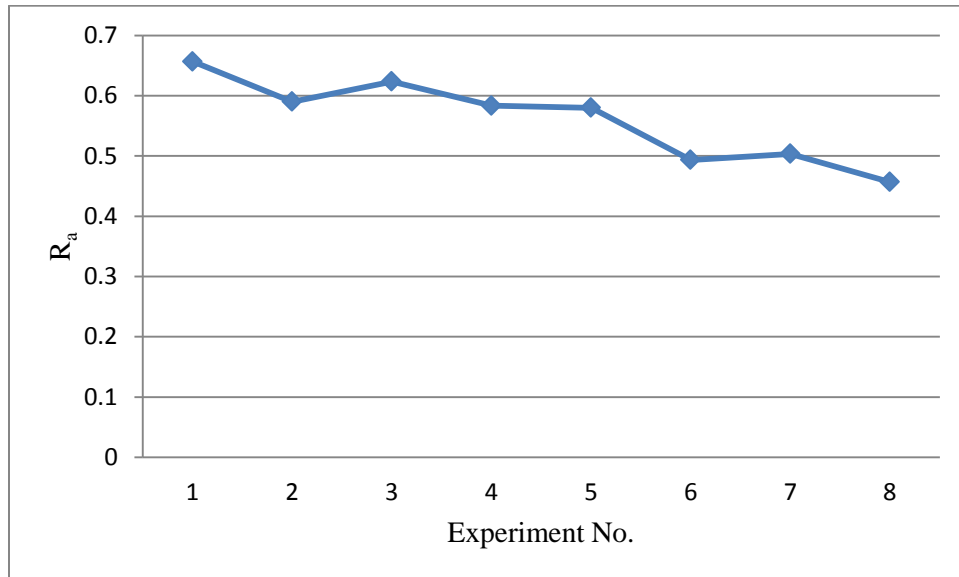


**Fig 4.10:** Variation of  $R_a$  w.r.t rolling parameter for rolling done using clay in mineral oil for AA-6101

Given below table provides the experimental values of surface roughness of AA-6101 cold rolled by adding nano-clay particles in Servosteerol C 4 lubricant.

**Table 4.11:** Surface roughness values for AA-6101 cold rolled by adding nano-clay particles in Servosteerol C 4 lubricant.

Exp. No.	% of clay	No. of passes	Roll gap (mm)	R <sub>a</sub> (1)	R <sub>a</sub> (2)	R <sub>a</sub> (3)	Average R <sub>a</sub> (μm)
1	1	5	3.0	0.68	0.63	0.66	0.66
2	1	5	2.4	0.59	0.61	0.57	0.59
3	1	10	3.0	0.66	0.6	0.61	0.62
4	1	10	2.4	0.55	0.58	0.62	0.58
5	2	5	3.0	0.64	0.58	0.52	0.58
6	2	5	2.4	0.52	0.47	0.49	0.49
7	2	10	3	0.49	0.49	0.53	0.50
8	2	10	2.4	0.48	0.43	0.46	0.46



**Fig 4.11:** Variation of R<sub>a</sub> w.r.t rolling parameter for rolling done using clay in water oil for AA-6101

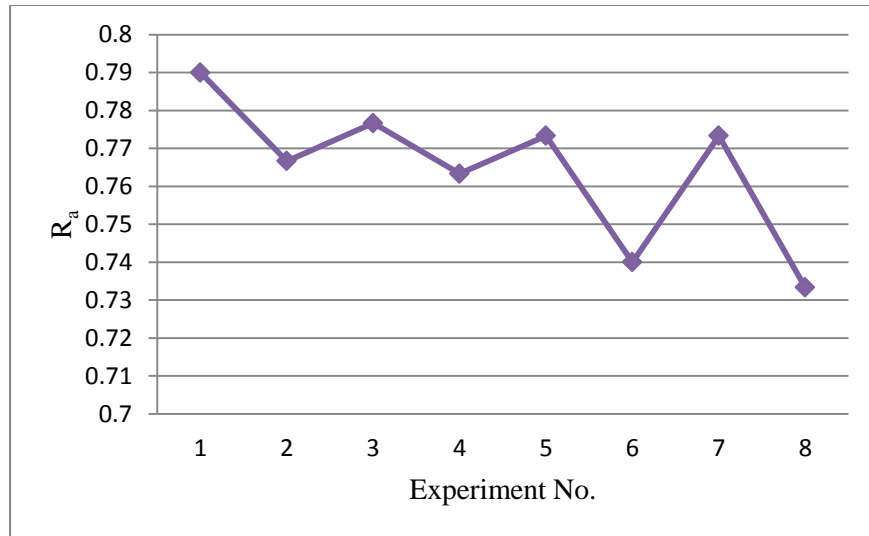
It has been observed by increasing the clay content in water based oil, the surface roughness decreases. But as compared to nanoparticles-mineral oil, the surface properties are poor in this case. This can be attributed to low viscosity of oil and agglomeration of particles which leads to increase in rolling forces and coefficient of friction.

From the above discussion it is very much clear the increase in clay content in the lubricating oil increases the surface quality. Addition of clay helps in improving anti-friction, anti-wear properties.

On the other hand, minor reduction in values of surface roughness of mild steel has been observed by the addition of clay in lubricant. Table 4.12 provides the experimental values of surface roughness of Mild Steel cold rolled by adding nano-clay particles in Servorol light lubricant and Table 4.13 provides the same in Servosteerol C 4 lubricant.

**Table 4.12:** Surface roughness values for Mild Steel cold rolled by adding nano-clay particles in Servorol Light lubricant.

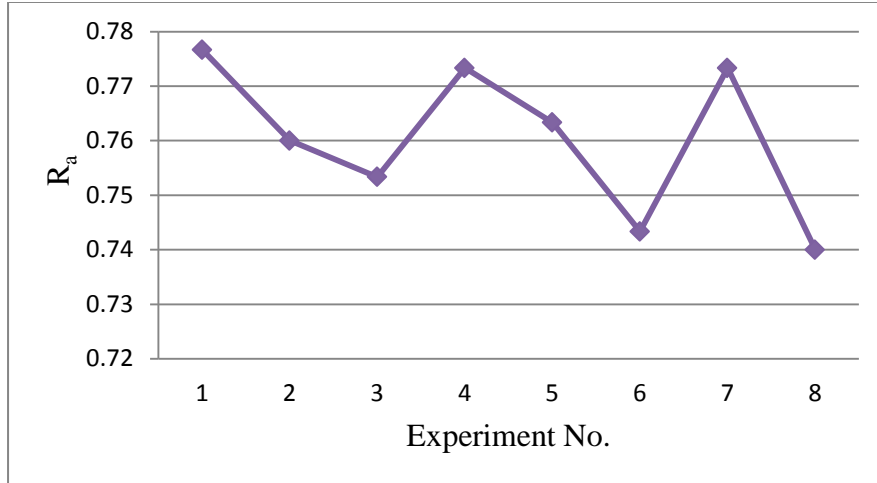
<b>Exp. No.</b>	<b>% of clay</b>	<b>No. of passes</b>	<b>Roll gap (mm)</b>	<b>R<sub>a</sub> (1)</b>	<b>R<sub>a</sub> (2)</b>	<b>R<sub>a</sub> (3)</b>	<b>Average R<sub>a</sub> (µm)</b>
1	1	5	3.0	0.77	0.82	0.78	0.79
2	1	5	2.4	0.8	0.74	0.76	0.76
3	1	10	3.0	0.84	0.73	0.76	0.77
4	1	10	2.4	0.81	0.77	0.71	0.76
5	2	5	3.0	0.75	0.76	0.81	0.77
6	2	5	2.4	0.72	0.76	0.74	0.74
7	2	10	3.0	0.77	0.79	0.76	0.77
8	2	10	2.4	0.72	0.7	0.78	0.73



**Fig 4.12:** Variation of  $R_a$  w.r.t rolling parameter for rolling done using clay in mineral oil for Mild Steel

**Table 4.13:** Surface roughness values for mild steel cold rolled by adding nano-clay particles in servosteerol C 4 lubricant.

<b>Exp. No.</b>	<b>% of clay</b>	<b>No. of passes</b>	<b>Roll gap (mm)</b>	<b><math>R_a</math> (1)</b>	<b><math>R_a</math> (2)</b>	<b><math>R_a</math> (3)</b>	<b>Average <math>R_a</math> (<math>\mu\text{m}</math>)</b>
1	1	5	3.0	0.77	0.8	0.76	0.77
2	1	5	2.4	0.79	0.74	0.75	0.76
3	1	10	3.0	0.8	0.71	0.75	0.75
4	1	10	2.4	0.81	0.78	0.73	0.77
5	2	5	3.0	0.75	0.76	0.78	0.76
6	2	5	2.4	0.73	0.76	0.74	0.74
7	2	10	3.0	0.77	0.79	0.76	0.77
8	2	10	2.4	0.72	0.72	0.78	0.74



**Fig 4.13:** Variation of  $R_a$  w.r.t rolling parameter for rolling done using clay in water based oil for Mild Steel

#### 4.4 Micro Hardness Evaluation

Micro hardness values at three different positions were taken on the rolled sample. Indentation was done by applying load of 200gm for AA-6101. Micro hardness value for aluminium alloy is presented in the table 4.14.

**Table 4.14:** Micro hardness values for AA-6101

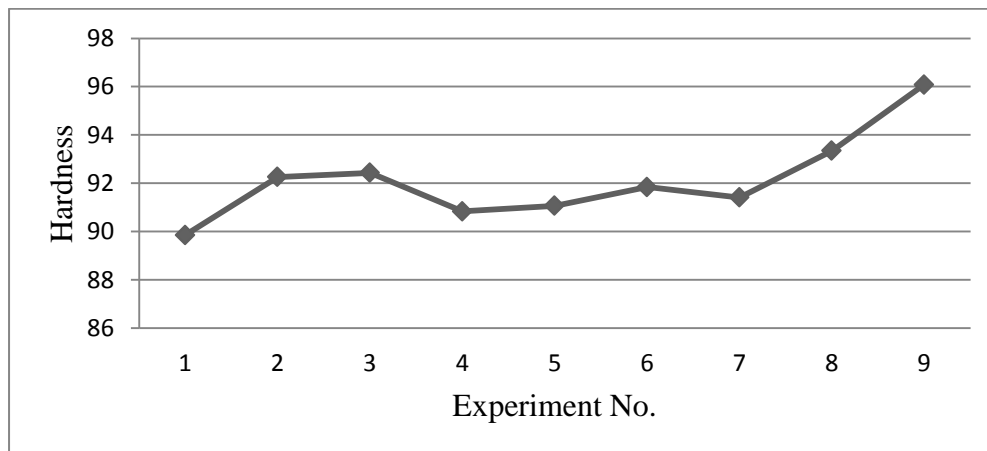
Material	Average Hardness (Vickers)
AA-6101	80-81

**Table 4.15:** Micro hardness values for cold rolled AA-6101

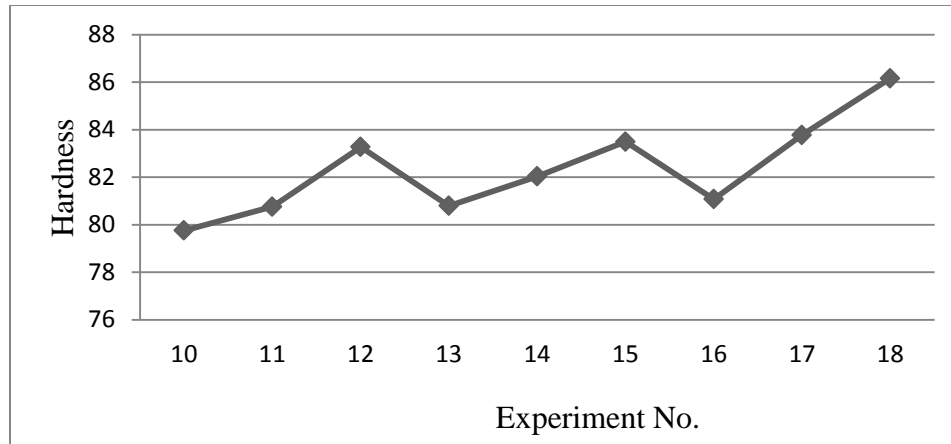
Exp No.	Lubricant	No. of passes	Roll gap (mm)	Hardness (1)	Hardness (2)	Hardness (3)	Average Hardness
1	No lubrication	5	3	88.45	91.83	89.26	89.85
2	No lubrication	5	2.4	88.32	96.22	92.21	92.25

3	No lubrication	5	1.8	91.21	92.96	93.11	92.42
4	No lubrication	10	3	81.40	97.52	93.56	90.83
5	No lubrication	10	2.4	83.43	93.35	96.39	91.06
6	No lubrication	10	1.8	90.15	93.56	91.80	91.84
7	No lubrication	15	3.0	90.53	93.40	90.29	91.41
8	No lubrication	15	2.4	94.44	92.30	93.27	93.34
9	No lubrication	15	1.8	96.65	94.25	97.32	96.07
10	Servorol light	5	3.0	80.61	80.13	78.52	79.75
11	Servorol light	5	2.4	81.61	83.13	77.52	80.75
12	Servorol light	5	1.8	83.06	81.36	85.36	83.26
13	Servorol light	10	3.0	86.25	80.61	75.51	80.79
14	Servorol light	10	2.4	80.85	81.85	83.37	82.03
15	Servorol light	10	1.8	81.70	83.82	84.95	83.49
16	Servorol light	15	3.0	87.25	80.51	75.45	81.07
17	Servorol light	15	2.4	88.97	83.03	79.32	83.77

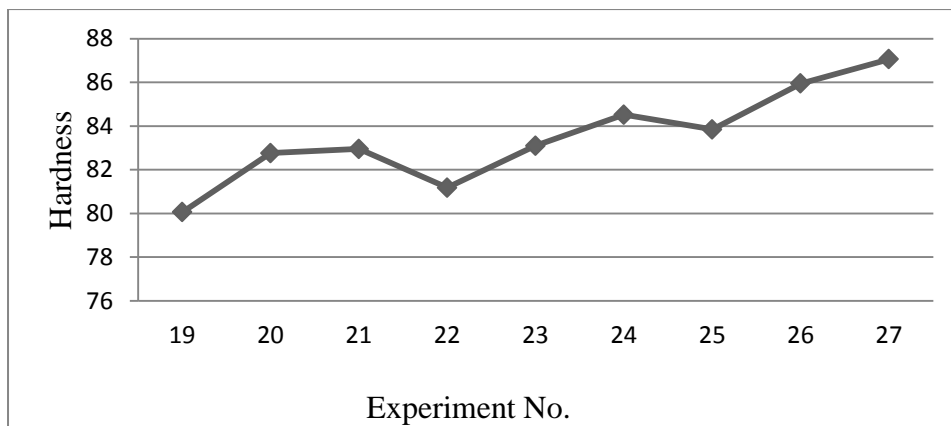
18	Servorol light	15	1.8	88.45	82.61	87.39	86.15
19	Servosteerol C 4	5	3.0	79.06	81.89	79.21	80.05
20	Servosteerol C 4	5	2.4	82.09	84.89	81.30	82.76
21	Servosteerol C 4	5	1.8	80.58	83.32	84.93	82.94
22	Servosteerol C 4	10	3.0	80.27	83.21	80.03	81.17
23	Servosteerol C 4	10	2.4	83.09	84.89	81.30	83.09
24	Servosteerol C 4	10	1.8	84.52	79.25	89.76	84.51
25	Servosteerol C 4	15	3.0	85.27	83.21	83.03	83.84
26	Servosteerol C 4	15	2.4	87.01	82.45	88.36	85.94
27	Servosteerol C 4	15	1.8	87.87	87.04	86.25	87.05



**Fig 4.14:** Variation of Hardness w.r.t rolling parameter for rolling done in dry conditions for AA-6101



**Fig 4.15:** Variation of Hardness w.r.t rolling parameter for rolling done using mineral oil for AA-6101



**Fig 4.16:** Variation of Hardness w.r.t rolling parameter for rolling done using water based oil for AA-6101

From the above graphical interpretation the following results were obtained:

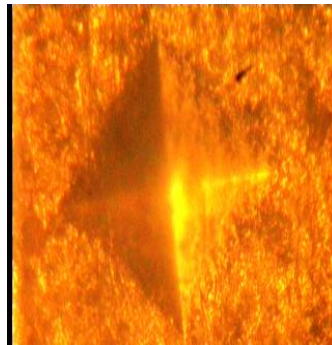
For experiment number 1 to 9 the hardness value increases with increase in thickness reduction. There is very small margin in hardness values of experiment number 2 and 3 because dislocations per materials volume remain unchanged or very slightly changed. But for dry condition trend is uneven.

For experiment number 10 to 18 the hardness value increases with decrease in roller gap or with increase in thickness reduction. A regular trend is achieved after every three experiments although more hardness is achieved in dry condition rolling, due to the more strain hardening of the work materials. Rolling force decreases due to decrease in coefficient of friction which leads to decrease in load applied on sheet and further decreases the alignment of grains.

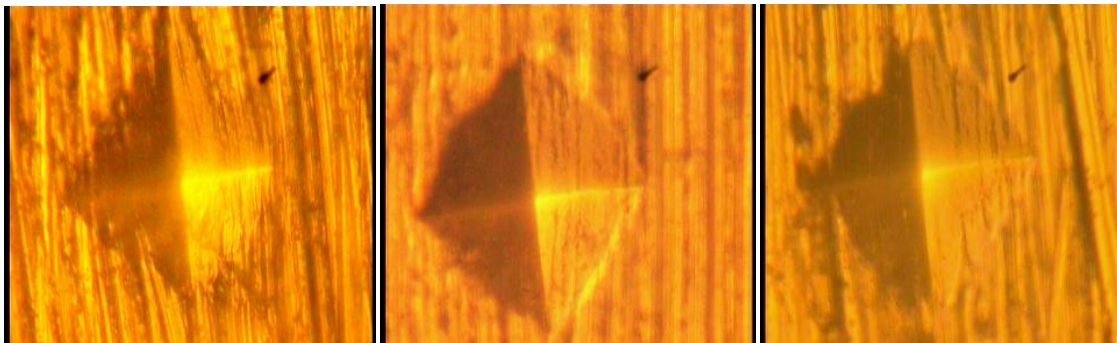
For experiment number 19 to 27 the hardness value lies between the values achieved from dry condition rolling and rolling done using mineral based oil. Trend is somehow mixture of Fig 4.14 and Fig 4.15.

Hence if rolling is done with or without lubrication, in order to obtain maximum hardness value roller gap should be less and number of passes should be more because it leads to increase in roll pressure which further impacts on strain hardening and results in grain orientation i.e. increase in dislocation density with plastic deformation. It leads to reduce the average distance between dislocations and dislocations start blocking the motion of each other and hence material gets harder. [<http://web.pdx.edu/~pmoeck/phy381/coldworking.pdf>].

Fig 4.17 shows the indent on AA-6101 (without rolling) and Fig 4.18 shows the indent on rolled regions of various cold rolled AA-6101 sheets



**Fig 4.17:** Micro hardness indenter for un-rolled AA-6101



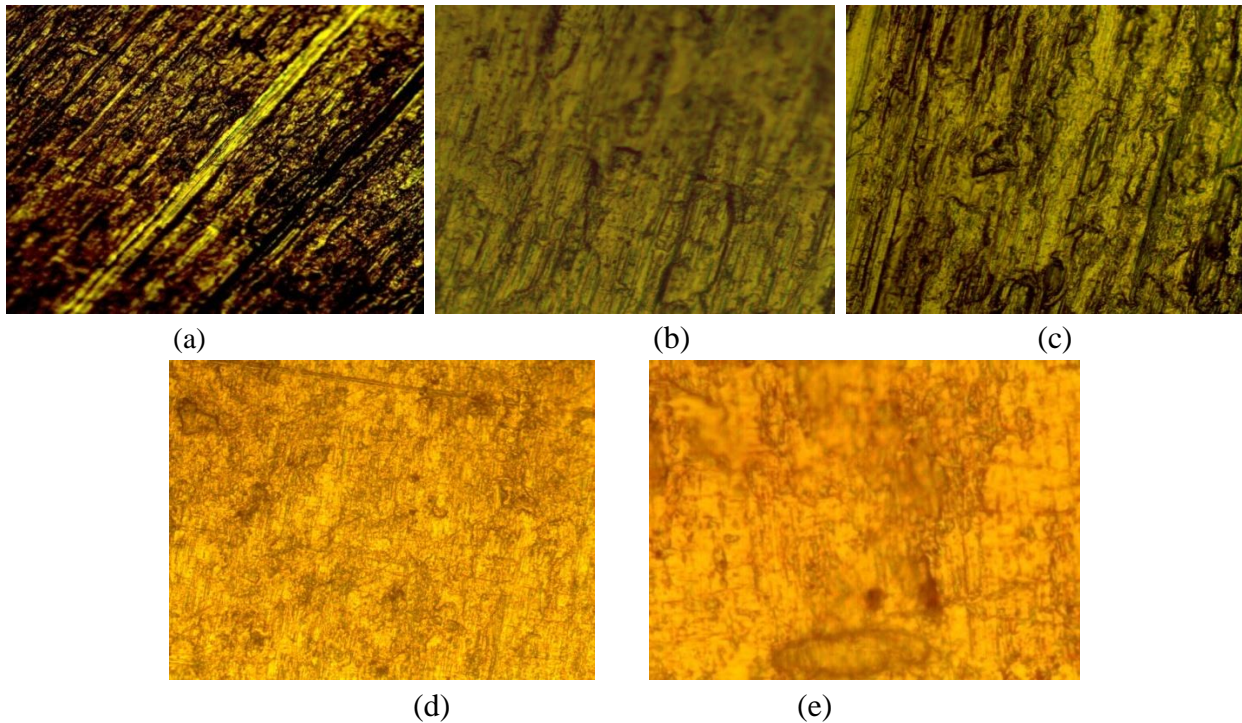
**Fig 4.18:** Micro hardness indenter for rolled AA-6101

## 4.5 Surface morphology and Microstructure

### 4.5.1 Surface morphology

Surface morphology is done in order to study the surface features like surface quality, surface topography, surface defects etc. Metallurgical microscope and Scanning electron microscopy (SEM) was used to acquire information of rolled surface.

Following are some micrographs of cold rolled AA-6101 obtained using Lieca's metallurgical microscope. From these micrographs it is very easy to characterize the surface of rolled sheets. The comparison between the rolling conditions can be easily studied by evaluating these micrographs.



**Fig 4.19** (a) Surface Of Cold Rolled AA-6101 in dry conditions, (b) Surface Of Cold Rolled AA-6101 Using Mineral Based Oil, (c) Surface Of Cold Rolled AA-6101 Using Water Based Oil, (d) Surface Of Cold Rolled AA-6101 using clay in mineral oil for AA-6101, (e) Surface Of Cold Rolled AA-6101 using clay in water based oil for AA-6101

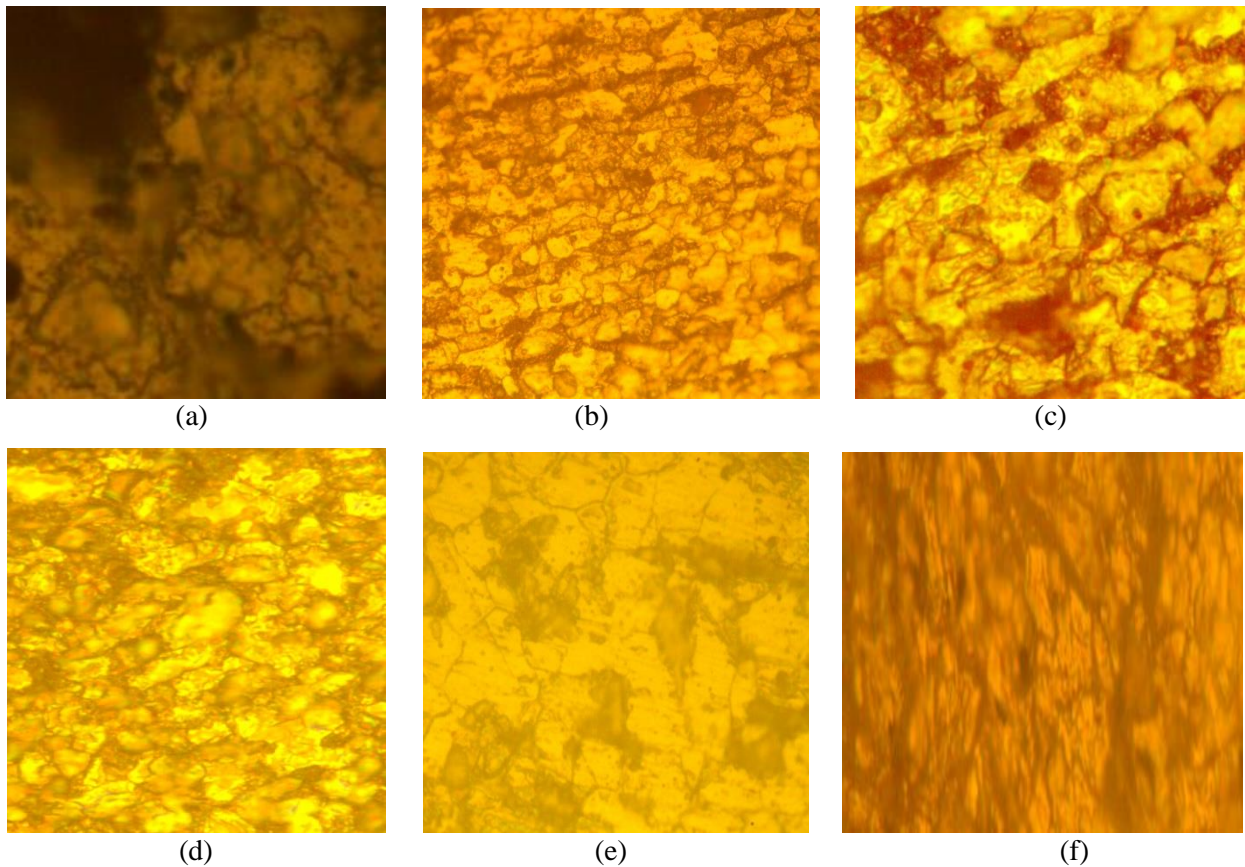
The above micrographs depict the same rolling parameters but the only difference is in lubricating conditions and captured at magnification scale of x500.

It has been observed that less pitting and scratches are there in Fig 4.19(b) due to the use of mineral based oil. It proves that more the viscosity of oil lesser is the roughness transfer from roller to sheet. Morphological properties of cold rolled AA-6101 were analyzed and it was

observed better surface with less pitting and micro crack defects was obtained. Experimental results specified that nano-clay particles as the additive used in cold rolling lubricant were capable to improve the wetting property, friction-reducing, anti-wear, and extreme pressure performance of the base metal strip. At the same time, nano-clay particles proved better lubricity to the cold-rolled strips.

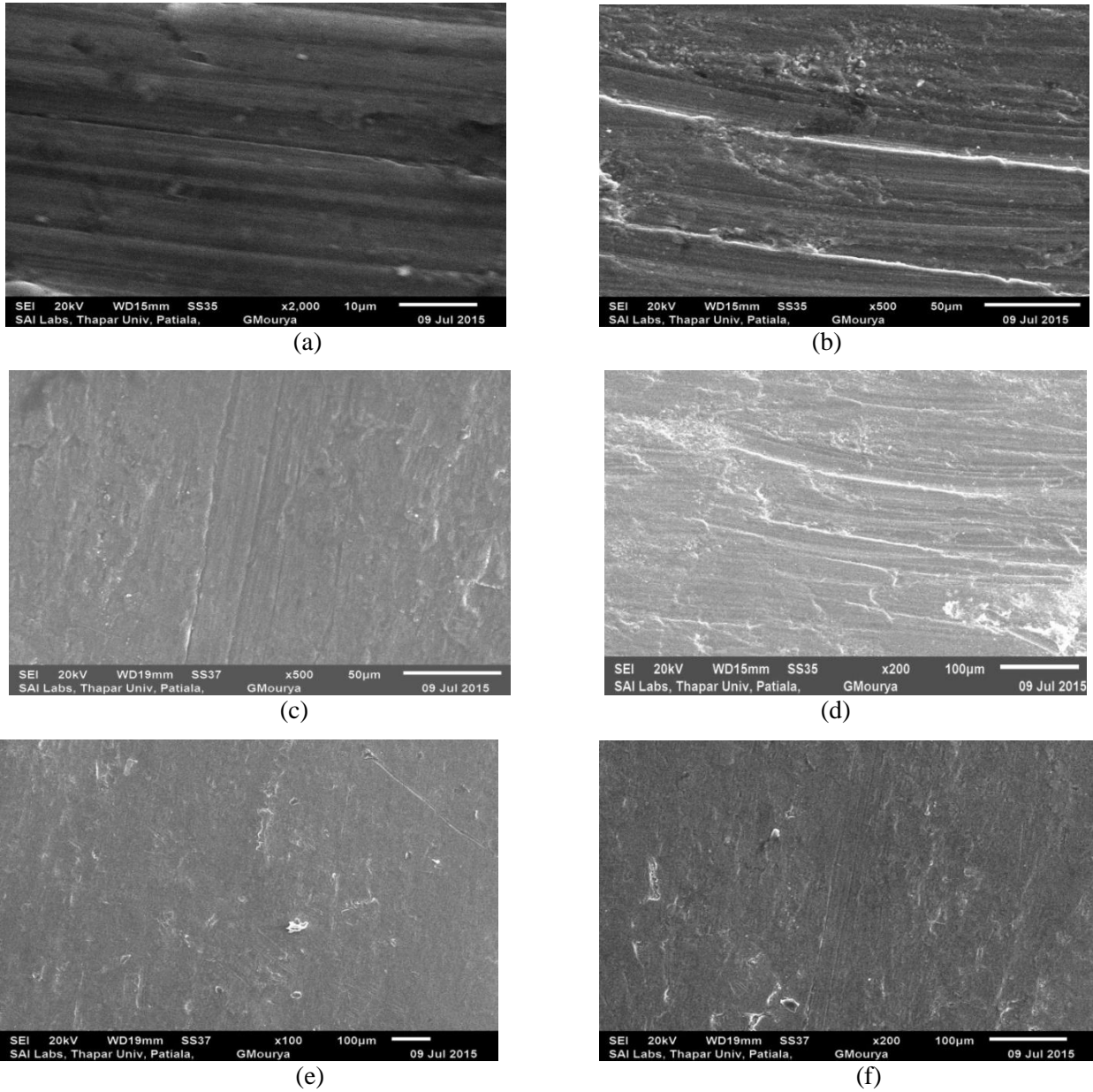
#### 4.5.2 Micro structural analysis

The microstructures were investigated in the longitudinal rolling direction with the help of metallurgical microscope and additional information from SEM micrographs. All microstructures were captured at magnification scale of x500. It shows grain deformations and realignments of strips with different rolling conditions.



**Fig 4.20:** Microstructure of cold rolled AA-6101 in different lubricating conditions. (a) Un-rolled AA-6101, (b) Cold rolled AA-6101 in absence of lubricant, (c) Cold rolled AA-6101 in presence of mineral oil as lubricant, (d) Cold rolled AA-6101 in presence of water based oil as lubricant, (e) Cold rolled AA-6101 in presence of clay particles added in mineral oil, (f) Cold rolled AA-6101 in presence of clay particles added in water based oil.

Fig 4.21 shows the various SEM images of cold rolled AA-6101 samples in different rolling conditions.



**Fig 4.21** SEM images for cold rolled AA-6101 in different rolling conditions. (a) Un-rolled AA-6101, (b) Cold rolled AA-6101 in absence of lubricant, (c) Cold rolled AA-6101 in presence of mineral oil as lubricant, (d) Cold rolled AA-6101 in presence of water based oil as lubricant, (e) Cold rolled AA-6101 in presence of clay particles added in mineral oil, (f) Cold rolled AA-6101 in presence of clay particles added in water based oil.

From the above displayed SEM images it is very much clear that after cold rolling surface roughness has been decreases. Fig 4.21(f) shows the best result because of using clay as additive in mineral oil.

# Chapter 5

## Conclusions

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### 5.1 Introduction

Due to the ever increasing demand for high quality strips and foils, lubricants are playing an important role in attaining the best possible rolled surface during the aluminum and steel cold rolling process. This research work helps us in understanding the influence of contact conditions and process parameters in improving the surface quality of aluminium and steel metals. It has also investigated the effect of nanolubricants for the improvement of the surface finish of work materials in cold rolling. These are illustrated in this report by using Al alloys and steel as rolled strips and two types of lubricants and a nanoparticles additive. Thus, the effects of oil film on the surface roughness, variation in rolling force, thickness reduction, rolled surface morphology, mechanical properties, etc, were investigated in this work during cold rolling of aluminum and steel strips. Various lubricants with different viscosities were used for the study. The performance of water-based and mineral based lubricant is compared with rolling done without lubrication. From the study it is revealed that lubrication has significant impact on rolling outcome and surface features of rolled strips, including strip reduction and spreading of strip, amount surface transfer layer and surface roughness transfer and hardness of the rolled strips. The following section incorporates the concluding remarks based on the results and discussion of our works.

### 5.2 Conclusion

The following conclusions are made from the study carried out so far to know the post effects of cold rolling done in different conditions on surface features of rolled sheets.

- 1) It has been found from our work that more is the viscosity of lubricant better is the quality of surface obtained after cold rolling.
- 2) Strip reduction and spreading of strip increases with raise in coefficient of friction and with the application of lubricant both strip reduction and spreading of strip decreases.

- 3) It has been concluded that less surface roughness transfer from roller surface takes place in rolling done in presence of lubrication. By using Servorol light as lubricant for cold rolling better surface quality is achieved as compare to dry rolling and rolling done using Servosteerol C4.
- 4) More the viscosity of lubricant better is the quality of surface obtained after cold rolling. Servorol light is more viscous than Servosteerol C4 and shows appropriate results. Dense lubricant and helps in decreasing the pitting defect.
- 5) Surface roughness decreases with increase in number of passes and decrease in roller gap.
- 6) Also, a theoretical analysis on strip surface roughness is carried out where experimental data are validated with an existing roughness model. A great number of statistical results show that experimental data is in excellent agreement with the adopted model and the relative deviation on roughness between calculated and measured is very less. New coefficients of surface roughness model have been derived to incorporate the effect of lubrication in a simplistic way, for cold rolling in lubricated conditions.
- 7) Also, a preliminary investigation is made for the formulation of nano lubricants by adding nano-clay particles to improve the surface finish. The amount of clay content has significant effect on the surface finish of the rolled surface.
- 8) It is found that hardness of cold rolled sheets is less effected by the presence of lubrication.

### **5.3 Scope of future work**

In addition to present work further work can be carried out in following directions:

- 1) Further work can be carried out to develop roughness model for fully formulated lubricated cold rolling process involving aluminium sheets.
- 2) Formulating a lubrication package to achieve the optimized coefficient of friction and roll-wear which in turn will produce a better surface quality in an economic manner.
- 3) Addition of nano particles either to improve the specific properties of lubricants or to functionalize the rolled surface after cold rolling.

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