THE EFFECTS OF COLD DEFORMATION ON THE MICROSTRUCTURES AND HARDNESS PROPERTIES OF 316L STAINLESS-STEEL

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DECLARATION

I hereby declare that this project report entitled 'The Effects of Cold Deformation on the Microstructure and Hardness Properties of 316L Stainless Steel' is the result of my own works except as cited in the references.

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Date	:	9 JANUARY 2022

APPROVAL

I hereby declare that I have read this project report. In my opinion, this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Automotive).

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Date	:	9 JANUARY 2022

DEDICATION

It is with my deepest gratitude and warmest affection that I dedicate this project report

To my beloved parents, family and to everyone who loves me endlessly.

ABSTRACT

This research discusses mainly on cold deformation impacts on the microstructural transformation and the hardness properties of the studied material which is 316L Stainless Steel. A total of five cold rolled samples were prepared accordingly with thickness reduction percentages increased from 0% to 40%. Microstructural modifications of the CR samples were examined under optical microscope image analyser at 10X magnification and the hardness test was carried out by utilising Vickers Hardness Tester equipped with a 0.5kg test load. From the metallurgical test, the results showed that as the thickness reduction percentage (%RT) increased, the content of martensite formation in 316L Stainless Steel also increased and thus, contributing to the enhancement of strength and reduction in ductility of the material. For the polished sample, the Vickers hardness at 0% RT is 165.9 and was increased to the maximum of 337.9 at 40% RT. As for the unpolished sample, the Vickers hardness at 0% RT is 176.2 and was increased to the maximum of 394.7 at 40% RT. In comparison, the micro-hardness reading of the samples (which was taken directly after cold rolling process) before polishing has slightly higher values than after polishing. From the results obtained, it is found that as the cold rolling reduction percentage increased, the content of martensite increased as well as the hardness properties of the studied material.

ABSTRAK

Kajian ini membincangkan tentang kesan-kesan kaedah 'ubah bentuk sejuk' (cold deformation) ke atas perubahan mikrostruktur dan sifat kekerasan bahan yang dikaji iaitu keluli tahan karat 316L. Sejumlah lima sampel telah disediakan secara tertib dengan peratusan pengurangan ketebalan yang ditingkatkan dari 0% sehingga 40%. Perubahan bentuk mikrostruktur telah dikaji dengan menggunakan mikroskop optikal penganalisa gambar dengan kanta 10X dan ujian kekerasan dilakukan dengan menggunapakai mesin ujian kekerasan Vickers dilengkapi dengan 0.5kg beban uji. Menurut apa yang diperolehi daripada ujian metalurgi, keputusan menunjukkan bahawa apabila peratusan pengurangan ketebalan meningkat, kandungan pembentukan martensit di dalam keluli tahan karat 316L juga telah meningkat. Nilai kekerasan Vicker bagi sampel belum digilap meningkat dari 165.9 (0% RT) hingga 337.9 (40% RT) manakala nilai kekerasan sampel yang telah digilap meningkat dari 176.2 (0% RT) hingga ke 394.7 (40% RT). Sebagai perbandingan, hasil bacaan kekerasan sampel (yang diambil secara langsung setelah proses penggolekan sejuk) sebelum digilap didapati mempunyai nilai bacaan yang lebih tinggi sedikit berbanding dengan yang selepas digilap. Berdasarkan keputusan diperolehi, kajian mendapati bahawa apabila peratusan pengurangan ketebalan meningkat, kandungan martensit bahan dan sifat kekerasan bahan juga meningkat.

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LIST OF ABBREVIATIONS

ASS - Austenitic Stainless Steel

ASTM - American Society for Testing and Materials

CR - Cold-Rolled

CNC - Computer Numerical Control

EBSD - Electron Backscattered Diffraction

EDS - Energy Dispersive X-Ray Spectroscopy

HV - Vickers Hardness

RT - Thickness Reduction

SEM - Scanning Electron Microscopy

SFE - Stacking Fault Energy

SS - Stainless Steels

WT - Weight

XRD - X-Ray Diffraction

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Austenitic stainless steels (ASS) are broadly used in medical field, transportation, food, nuclear and the petrochemicals industry. This is due to the fact that austenitic stainless steels are well-known to have high corrosion resistance, high strain hardening, great plasticity and formability. On the other hand, austenitic stainless steel has relatively low yield strength. Thus, the applications of this material in some areas like automotive industry and structural engineering are very limited.

Mechanical properties of the material like the strength of the austenitic stainless steel can be significantly increased in several ways such as cold deformation strengthening, grain size strengthening, bake hardening strengthening and many more. Amongst all these methods, cold deformation strengthening is best believed as a practical way and fits the industrial applications because of the high strain hardening of austenitic stainless steel. It is also considered as the best technique for manufacturing of products that are sizeable and has the benefit of cost-effective (Xiao Li *et al.* 2019).

Cold working; for example cold rolling means a process where metal is strengthened by changing its shape without the presence of heat. The microstructures changes during cold rolling process of austenitic stainless steels may involve; the stacking fault occurrence, deformation bands, ε-martensite, deformation twinning and α'-martensite, the evident grain subdivision and the dislocation multiplication. (Xiao Li *et al.* 2019).

These features will add more complexity of dislocation motion and consequently will cause the steel to be strengthened. The microstructural modification from the austenitic into martensitic can increase the mechanical properties of cold-rolled austenitic stainless steels. Microstructural analysis exhibits that cold deformation causes major microstructural modifications in austenitic stainless steel, especially hardening. (Maria *et al.* 2011).

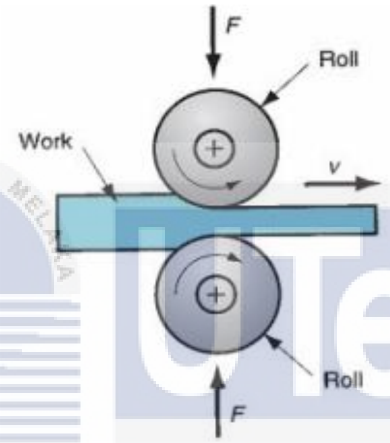

Figure 1.0: Cold rolling process.
(Source: Fundamental of Modern Manufacturing Materials, 4th Ed.)

Cold working has the advantage of producing a smooth surface finish on the product as well as improving the material's strength and hardness properties. Since no heating of the material is required in cold working, it saves money. This process does not only have superior dimension control it also provides better reproducibility and interchangeability of parts.

However, cold working requires a high amount of force to begin and end the work. It also requires high strength and precision of the equipment, large motor power, and high energy consumption.

Table 1.0: Stainless steel groups and their general characteristics.
(Souce: Unifiedalloys.com)

Alloy Group	Magnetic Response	Work Hardening Rate	Corrosion Resistance	Hardenable	Ductility	High Temperature Resistance	Low Temperature Resistance	Weldability
Austenitic	Generally No	Very High	High	By Cold Work	Very High	Very High	Very High	Very High
Duplex	Yes	Medium	Very High	No	Medium	Low	Medium	High
Ferritic	Yes	Medium	Medium	No	Medium	High	Low	Low
Martensitic	Yes	Medium	Medium	Quench & Temper	Low	Low	Low	Low
Precipitation Hardening	Yes	Medium	Medium	Age Harden	Medium	Low	Low	High

The microstructure modifications of austenitic stainless steel during cold rolling process is significantly based on stacking fault energy (SFE). The phase alteration in austenitic stainless steels is restrained due to austenite phase stability which is dependent on the Md30 temperatures (temperature where half of martensite changed from austenite after one-third tensile deformation).

Commonly, austenite phase in austenitic stainless steels is an unstable phase where during the plastic deformation phase, martensite is transformed to strain-induced martensite. Martensitic phase normally shows a greater strength and less plasticity. Referring to Deming *et al.* (2018), some austenitic stainless steels for example 316L stainless steels have higher content of alloy elements.

For this project, effects of cold deformation process on the microstructure and hardness properties of material 316L stainless-steels is studied. An optical microscopy will be used to examine the microstructural deformation as the cold rolling reduction increased and Vickers Hardness test will be carried out to obtain the hardness properties. The relationship between microstructure and hardness of the cold deformed steel will be analysed.

1.2 Problem Statements

The hardness and the ultimate tensile strength values in 316L stainless steels are relatively low. Austenitic stainless-steel cannot be hardened with thermal treatment since alloy content does not allow structural transformation. Low yield strength limits the application of austenitic stainless-steel in automotive industry and structural engineering. Cold rolling process is expected to enhance the mechanical properties of 316L stainless steel for broader applications in industry.

1.3 Objectives

1. To examine the microstructure modifications of the cold-deformed steel.
2. To analyse the hardness properties of the cold-deformed steel.
3. To study the relation between microstructure and hardness of the cold deformed steel.

1.4 Scope

This project follows the standards according to ASTM International. The as-received thickness of the test specimen is 2mm at 0% RT and it is increased to a maximum of 40% RT at maximum temperature of room temperature. To examine the microstructures, an optical microscopy with 10X and 20X magnifications is used. To analyse the hardness, Vickers Micro hardness tester is utilised with a 4.905N as the total load force and 10s as the dwell time.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of Cold Working and Hot Working.

Cold working and hot working are two significant methods and widely used in metallurgy in order to obtain metal products of desired properties. The above processes get their names according to the operating temperatures where they are conducted. Each technique yields a product that is somewhat distinct from the other. Cold rolling and hot rolling are the examples of these two metal strengthening method.

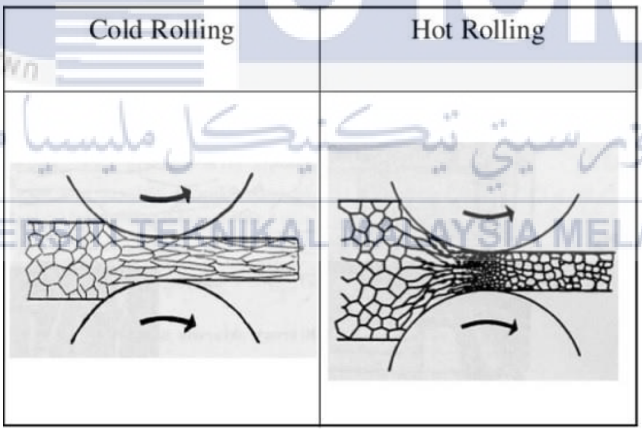

Figure 2.0: Cold rolling vs hot rolling.
(Source: LearnMech.com, 2022)

Cold working refers to a process of strengthening metals by plastic deformation which is done at temperatures below the recrystallization temperature of the metals. The majority of cold working processes are carried out at room temperature. Cold working works best with metals such as steel, copper, and also aluminium. Cold working reduces ductility.

Internal and residual stresses are generated in the metal during cold working (Madhu, 2018). The most popular technique of work hardening is known as cold rolling.

Hot working defines the process of permanent deformations of metals above their recrystallization temperature without causing strain hardening. Hot working is typically done at high temperatures. Hot working is can increase metal ductility and has the ability to reduce yield strength thus making it easier to work with metal. In hot working, the metal deforms and recovers at the same time. Residual stresses are not presented during the hot working process. (Madhu, 2018)

Recent writing on LearnMech.com (Sachin, 2022) described that hot rolling involves heating huge chunks of metal, such as slabs or steel billets, over their recrystallization temperature. An example for hot rolling is hot forging. The metal is subsequently compressed between rollers, resulting in thinner cross sections. The cross sections are thinner compared to all those made by the same number of stages of cold rolling techniques. Hot rolling additionally shrinks the average grain size of the metal while maintaining an equiaxed microstructure.

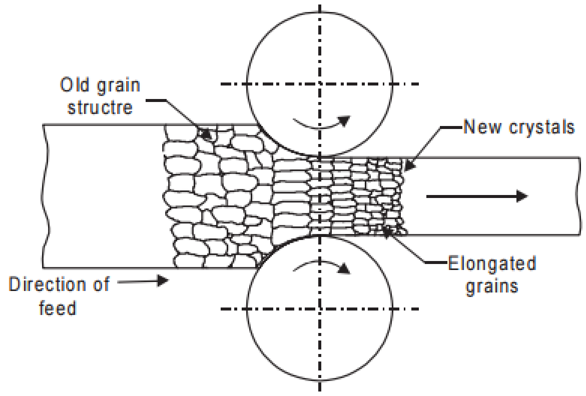

Figure 2.1: Grain transformation during hot forging.
(Source: Inspection-for-industry.com)

2.1.1 Cold Working: Cold Rolling Process

Cold working is a metal forming process in which the metal is deformed under its recrystallization temperature. In the vast majority of cases, cold working of metal is carried out at room temperature. Recrystallization temperature means the lowest temperature where plastically deformed metals creates new grains within the specified period. Majority of metals have a recrystallization temperature of 0.3 to 0.5 of their melting point. (López et al, 2012).

Cold rolling is a technique of metal forming in where metal is forced through a set of one or more rolling mills to achieve desired thickness or a decrease in thickness as the length increases. It is a hardening process that takes place below the metal's recrystallization temperature or, in most cases, at room temperature. After a metal has been hot rolled, it is usually cold rolled to produce nice finishing. It improves the stiffness and the tensile strength of the metal as well. (Kumar, 2021)

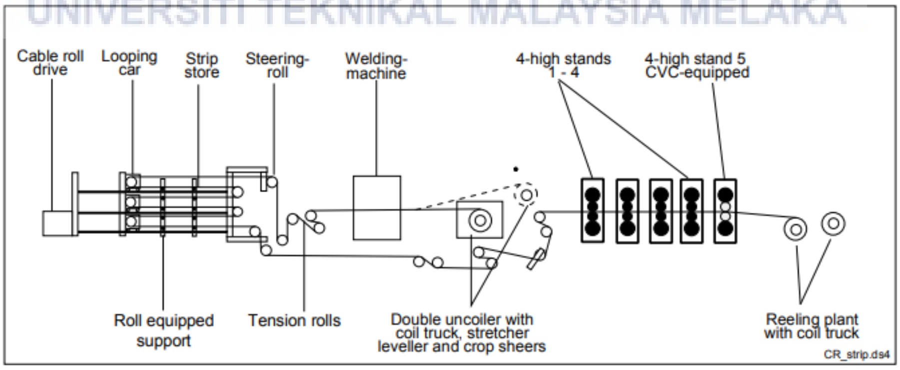

Figure 2.2: Diagrammatic view of a continuous cold rolling mill.
(Source: Jochum et al., 1999)

2.2 The Relationship between Cold Working and Deformation.

An example method of cold work is cold rolling where the process includes the metal being inserted in between a pair of rollers to reduce the thickness or to achieve uniform thickness of the metal. When it is passed through the rollers and is compressed, the metal grains will experience structural change known as deformation. As a metal goes through this process, permanent defects in the metal structure will appear and change their shape or crystalline makeup. These defects cause the reduction of the movement of the crystals within the metal. Hence, the metal becomes resistant to further deformation.

Discussion by Engineering Notes (Surupa, 2021) states that cold working provokes the distortions of crystal grains and inclusions in accordance with the metal flow. Slip is principally on primary glide planes in the initial phases of plastic deformation, and the dislocations will form coplanar arrays. Cross slip will occur as deformation develops. The cold-worked structure creates high dislocation density regions, which quickly develop into networks. At low deformation, the grain size will decrease with strain but quickly attains a fixed size.

2.2.1 Effect of Cold Deformation on the Formation of Austenite

At the present moment, the automotive industry is setting on a trend towards lightening vehicles in order to comply with the new regulations of exhaust emission control. This goal creates a large-scale challenge to steel manufactures all around the world. The trials and tribulations lies in manufacturing new materials (alloys) with the ideal strength, ductility and cost valuation for the multiple parts and components. (Goune *et al*., 2006).

Here, manipulation of the steel's microstructure on the smallest possible scale are likely to be the key to success. In this circumstances, the development of the inter-lamellar distance is an essential answer to the demand to weight reduction in the automotive industry. The cold deformation will affect both parameters: the inter-lamellar distance Dp and the spacing of pearlite bands Db. (Goune *et al*., 2006) A treatment allows for the consideration of the effect of deformation on Dp and Db. In point of fact, it is founded that:

$$Dp = Dp^{o} \exp\left(\frac{-\varepsilon p}{2}\right)$$

$$Db = Db^{o} \exp(-\varepsilon b)$$

Where εp and εf are the local deformations into pearlite and ferrite, respectively. The microstructures shown in Figures 2.3 demonstrate the effects of cold rolling on the pearlite band spacing as well as the inter-lamellar distance. As studied by Goune *et al.* (2006), the greater the cold reduction, the smaller the pearlite band spacing and inter-lamellar distance.

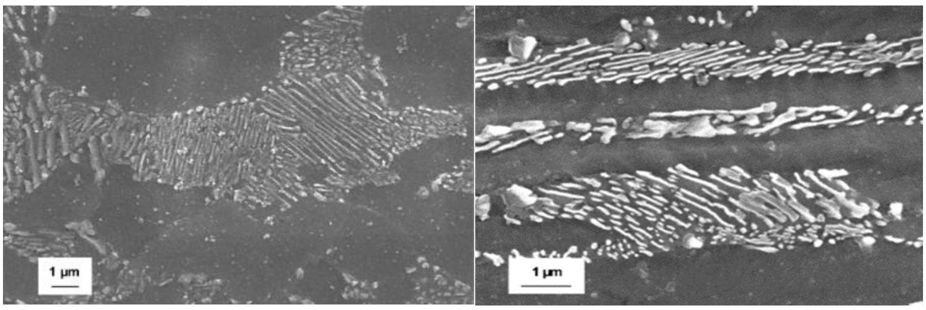

Figure 2.3: Initial microstructures for a cold reduction of 0% and 65%.
(Source: Revue de Métallurgie 103 (10), 2006.)

2.3 Residual Stress after Cold Rolling Process.

Cold-rolling processes are extensively applied in various manufacturing. Rolling-induced residual stresses have a major impact on the material's behaviour. Therefore, knowing this state is essential. The term residual stresses means the stresses that remain inside a structure once all forces applied have been eliminated. Tensile residual stress (positive) pulls the material away, whereas compressive residual stress (negative) pushes it together.

Residual stresses evolve when a material reaches equilibrium due to plastic deformation created by mechanical loads or thermal loads applied, as well as phase changes. Residual stresses form in metal and stay until eliminated by additional heat treatment. If residual stresses are eliminated by reheating well below crystallisation temperature, there is no noticeable change in the physical properties of the grain structure. Additional heating into the recrystallize range removes the influence of cold working and returns the metal to its original form.

Unwanted residual stress can cause stress corrosion cracking, distortions, and component premature failures. Heat treatment, controlled cooling, and localised heating are the approaches that can be used to minimize residual stresses that are possibly harmful. Even small deviations in residual stress can have a large impact on a component's life, hence this stress must be controlled to assure safety and to prevent failure. The initial residual-stress state effects on the final state after cold rolling can be examined by simulations of finite-element analysis (FEA) and X-ray diffraction (XRD).