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Investigating the Effect of Hot and Cold Working on the Microstructure and Mechanical Properties of Low-Carbon-Steel for Sustainable Manufacturing

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ABSTRACT

This project examines the impact of hot working and cold working on low-carbon steel. Low-carbon steel is widely used in industries due to its favourable strength and ductility characteristics. The study investigates how hot and cold working processes affect the material's mechanical characteristics and microscopic arrangement. Rigorous experimental tests were conducted on A36 low-carbon steel samples subjected to the hot working at 950°C and cold working at 20°C, and the samples were subjected to rolling, squeezing, and bending processes. The samples were then analysed using hardness testing, tensile testing, and optical microstructural analysis. The significance of this study is that they were able to analyse the microstructural and the stress and strain analysis from the samples. The results show that the Brinell hardness increases during the cold rolling process, having 349.011 BHN, compared to the hot rolling process, which has 330.89 BHN. Also, the hot bending process increases the hardness properties compared to cold bending, having 245.25 and 213.71 BHN, respectively. Also, the study shows that the squeezing process of the hot is 231.65, as opposed to 221.09 BHN of the cold squeezing process. Also, the hot rolling process increases the 11263.11 (N) load at the break for the tensile test, which is higher than the cold rolling, having 9471.7 (N). This goes the same way as the elastic modulus, having 31766.02 (MPa) and 27427.64 (MPa), and the hot rolling process increases the tensile stress at a zero slope of low carbon steel, having 907.45 (MPa) against 753.74 (MPa) for the cold rolling process. The study concluded that hot working improves formability, toughness, and ductility. In contrast, cold working increases strength and hardness, which can assist in producing a quality materials formulation for sustainable manufacturing of mechanical components made of low-carbon steel.

1. Introduction

In modern industries, affordable, high-strength steels are highly desired for their ability to reduce weight while also safeguarding the environment [1]. Hot deformation is required for steels to achieve higher mechanical properties and final microstructures. Deformation can cause a variety of

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metallurgical processes, including carbide precipitation, dislocation slip, deformation substructure evolution, dynamic recrystallisation (DRX), and grain boundary bulging and sliding [2]. These occurrences impact the material's final microstructure, mechanical properties, and flow behaviour. As a result, two key aspects are significant regarding hot deformation: flow stress curves, or, more precisely, the constitutive relationship of essential materials, and the impact of deformation on the evolution of microstructural features and mechanical properties [3]. Hot working is the plastic deformation of a metal. Hot working is the plastic deformation of a metal above its recrystallisation temperature [4]. The recrystallisation temperature is when deformed metal grains are replaced by flaw-free grains. Hot working occurs at temperatures higher than a metal's recrystallisation temperature, allowing it to undergo plastic deformation while concurrently recrystallising. However, this is accomplished below the metal's melting point. Also, through the crushing of extensive grain formations and the filling of any potential gaps, hot-working refines the steel structure. Plastic steel can be shaped through hammer blows or a drop stamp or flow more slowly and consistently when subjected to pressure from a hydraulic press [5]. There are different ways to modify materials, which involve both hot and cold working processes.

Cold working refers to a technique wherein the metal is deformed in a plastic manner at temperatures below its recrystallisation point. This process alters the mechanical properties of low-carbon steel, which typically contains less than 0.25% carbon by weight [6]. When low-carbon steel is cold-worked, its strength and hardness rise while its ductility and toughness fall. This is because cold working causes dislocations in the metal's crystal structure to become twisted, making it more difficult for them to pass each other. As a result, the metal gains strength and hardness while becoming more brittle. Rolling, drawing, bending, and forging are ways of cold-working low-carbon steel. Each process causes a particular deformation pattern in the metal, influencing its final properties [7]. In general, cold working procedures can help improve the mechanical properties of low-carbon steel, making it stronger and more wear-resistant. However, it is critical to carefully regulate the amount and kind of cold working since excessive deformation can cause cracking and other problems in the metal. Low-carbon steel refers to various metallic materials with a limited proportion of carbon within their alloy composition. With a carbon level ranging from 0.05% to 0.30%, manganese usually has a value of 0.40 to 1.5%, which is an economical option compared to other types of steel. Low-carbon steel is broadly used in numerous applications. Despite possessing properties that make it suitable for manufacturing various products, low-carbon steel is typically processed into flat-rolled steel sheets or strips.

Gao *et al.,* [8] investigated the warm rolling of a low carbon, low alloy steel with reductions ranging from around 30% to 70%. The steel was annealed at 450°C. Microstructure and compressive testing were used to characterise the microstructural evolution under strain rates of 1.0 × 10− 3–2.0 × 103 s − 1. When compared to tempered steel, microscopy examinations revealed that warm rolling produced ultrafine-grained structures with high-density dislocations and finer M3C carbides. Further annealing encouraged the precipitation of smaller carbides, which resulted in the recovery of dislocations and a slight coarsening of the grains. The findings of the compressive testing showed that the warm rolled steels' yield strengths at various strain rates were significantly higher—by about 40% to 70%—than those of the sample received. This increase was caused mainly by precipitation, grain boundary, and displacement strengthening. Following annealing, dislocation recovery and a modest increase in grain size caused the yield strength to fall marginally. Furthermore, the effects of microstructure changes, such as displacement densities, grain sizes, and carbide precipitations, on the strain rate dependence of steel strength were investigated during warm rolling and subsequent annealing [9].

The issue statement inquires about how the different processing circumstances of hot and cold working affect the mechanical properties of low-carbon steel, such as strength, ductility, toughness, and fatigue resistance. Processing conditions can alter grain size, texture, and residual stresses in steel, affecting its performance in the intended application. Understanding the effects of hot and cold working on low-carbon steel is vital to obtain the finished product's mechanical properties and optimise processing conditions. Chen *et al.,* [10] understand the microstructural changes: Both hot and cold working can affect the microstructure of low-carbon steel, causing grain refinement, texture development, and the introduction of residual stresses. Studying these changes can provide information on deformation mechanisms and how they affect steel's mechanical characteristics. Hot working alters the object's microstructure, producing small, spherical grains that enhance its engineering properties. These grains contribute to increased toughness, ductility, and material strength.

On the other hand, cold working is the process of shaping and resizing metal without heat, which results in greater strength and physical qualities. Mechanical stress on the metal at or near room temperature alters its crystalline structure, enhancing its strength. Cold-working also allows for metal deformation. This study investigates how low-carbon steel performs during cold and hot working operations. The effect of hot-working on the mechanical properties of low-carbon steel was investigated experimentally. Low-carbon steel's microstructure was examined to better understand the influence of cold working. A comparison investigation was carried out to determine the effect of hot and cold working processes on the mechanical properties of low-carbon steel. The addition to our understanding of hot and cold working on low-carbon steel is crucial because it provides insights into the behaviour and performance of this essential material under various processing circumstances. Understanding the effects of hot and cold working on low-carbon steel can improve manufacturing processes, product design, and material selection in various industries.

2. Methodology

2.1 Materials

This section entails the material employed for this research. The study uses low-carbon steel as the working material.

i. The sample of the low-carbon steel used for this study is the ASTM A36 low-carbon Steel**.** The carbon content, typically 0.05% to 0.29%, is classified as a low-carbon steel category. The chemical composition is shown in Table 1.
ii. Furnace or heating equipment was applied to subject the low-carbon steel materials to elevated temperatures.
iii. Cooling media: Water and oil quench were applied for cold working, which involves deforming the low-carbon steel at room temperature or slightly below. Depending on the specific cold working methods the author plans to use (e.g., rolling and bending).
iv. Mechanical deformation equipment: Cold working requires equipment such as a rolling mill, bending milling, and squelching process
v. Testing and analysis equipment: The tensile testing machines to measure mechanical properties, the microscopy tools (e.g., optical microscope) for microstructural analysis, and hardness testers for determining the hardness property of the materials

Table 1
The elemental composition of the ASTM A36 low-carbon steel

Elements	Weight %
Carbon ©	0.26%
Manganese (Mn)	0.75%
Copper (Cu)	0.2%
Phosphorus (P)	0.04%
Sulfur (S)	0.05%
Iron (Fe)	99%

2.2 Method

Typically, the methodology for studying the effect of hot and cold working on low-carbon steel involves combining experimental and analytical techniques. The following steps can be taken to conduct the study:

2.2.1 Procedure for hot and cold rolling

Hot and cold rolling operations employ distinct temperatures and rolling techniques [11]. During the hot rolling process, the steel is heated to a temperature higher than its recrystallisation temperature, usually between 850 and 1,200 degrees Celsius for most steels. The hot steel passes through a series of rollers that apply pressure to shape and mould the material. The rollers can be joined in various ways to produce different shapes and thicknesses. After forming the required shape, the steel can be cooled and regulated to improve its mechanical qualities. Cold rolling processes steel at room temperature or somewhat lower, often between 0 and 200 degrees Celsius. Figure 1 depicts the operation setup. The temperature employed in this study for the hot and cold rolling process is 950°C and 20°C, respectively, at a rate of 5 °C/s and held for 25 s to obtain a uniform temperature distribution. The K-type thermocouples were employed to obtain the temperature during the process. The cold rolling process typically entails putting the steel through a series of rollers several times, with each pass reducing the material's thickness. The rollers can be configured in various ways to generate different shapes and thicknesses, and the process is repeated until the desired thickness is achieved. The original dimensions of the specimens used are a diameter of 25 mm and a length of 120 mm. The cold rolling process may also incorporate other operations, such as annealing, to improve the material's properties. Hot and cold rolling require specialised equipment, such as rolling mills and furnaces, to get the desired results. Individual approaches for each approach may vary depending on the material being rolled, the desired end product, and other factors.

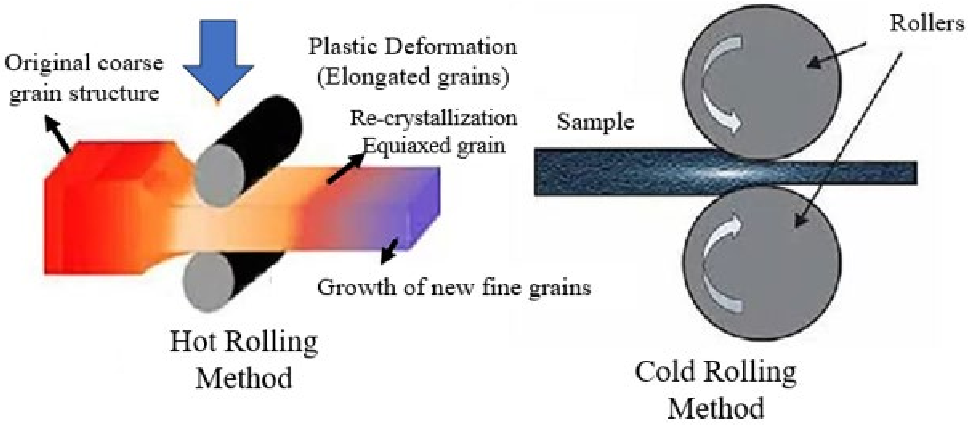
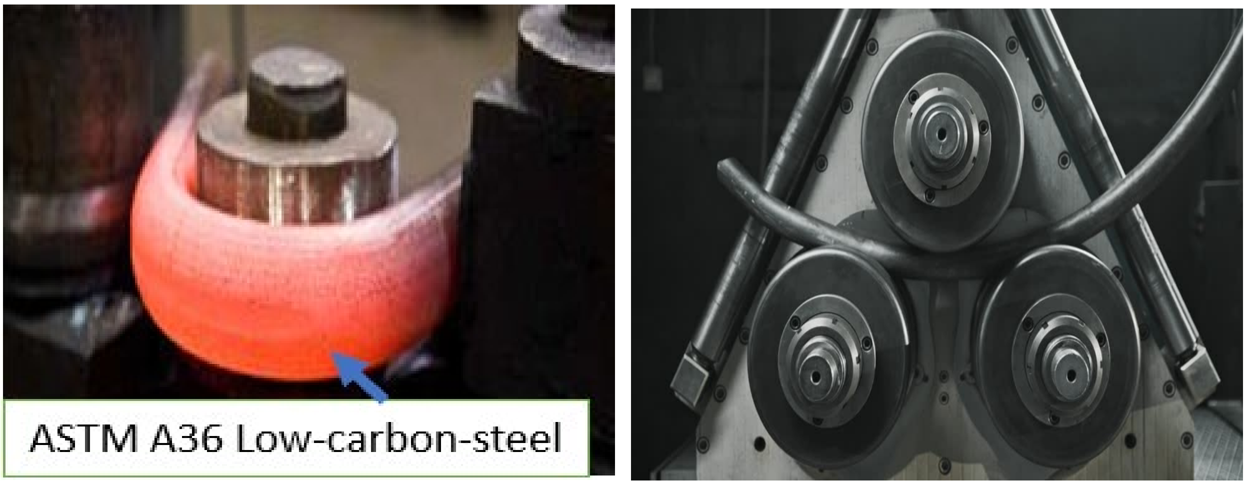


Fig. 1. The hot and cold rolling process of metals

2.2.1 Procedure for hot and cold bending

Hot bending is a process of heating a material to high temperatures, usually 850 to 1200oC, using a furnace to make it plastic to be easily shaped. Heating is followed by gradually bending the material to the correct contour with the help of corresponding instruments or equipment. The substance is then left to cool slowly by exposure to normal air, pouring water, or blowing air over it. This cooling procedure is essential because it helps retain the new shape of the material [12]. Cold bending is the practice of bending a material without having to heat it, that is, bending materials at a temperature close to the surrounding atmosphere. Blinders are used to ensure that the material does not shift when bending is being done. Hot bending is heating the material to a temperature of around 950oC (i.e. 850 to 1200 o C), using a furnace or torch to increase the material's ductility. After that, the heated material is gradually shaped to meet the required contour by various tools or the bending gear. The substance is left to cool slowly, either by cooling or washing with water or by air circulation. This horrifying process is essential if the material is kept in its newly formed shape [12]. Cold bending is a bending process by which a material is bent at a temperature not exceeding the ambient temperature. The material must be profiled, and clamps or other holder retainers bind the material for the entire bending process. Moreover, safety measures must be incorporated when operating both the hot and cold bending since working on heated materials or applying force on dangerous materials [13].



(a) (b)

Fig. 2. (a) Hot bending and (b) Cold bending process of steel

2.2.2 Procedure for tensile test

Heat-treated cylindrical rods with a diameter of 25 mm and a length of 110 mm were used to create the tensile specimens. According to ASTM E-8M, tensile specimens with a circular cross-section diameter of 12.5 mm and a gauge length of 25 mm are machined; the dimensions are shown in Figure 3. During the experimental process, a constant displacement rate is applied to the specimen during the test while load and displacement data are recorded. The test continues until the specimen fractures or reaches the desired level of deformation or strain. The recorded data can be used to derive engineering stress and strain values, tensile strength and other mechanical parameters following the testing standard [14]. It is vital to repeat the test on many specimens and follow the relevant standards [15].

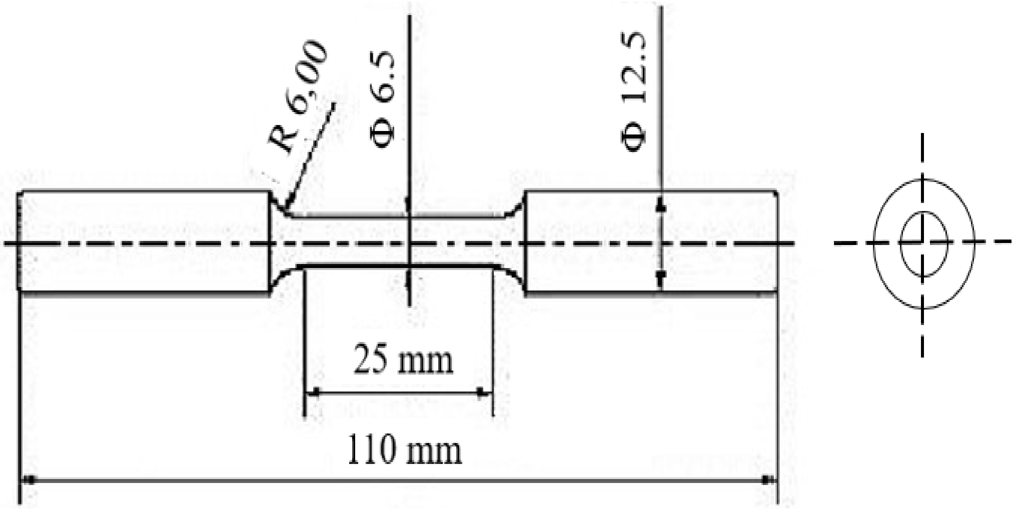


Fig. 3. The tensile test specimen

2.2.3 Procedure for hardness and impact test

Hardness and impact tests determine the toughness and resistance to deformation of a material, such as low-carbon steel, under impact loading. This test yields valuable information about the material's ability to absorb energy and withstand fracture. The experiment employs a typical sample of low-carbon steel with the necessary dimensions and form. Cut or machine the samples into suitable specimens, such as rectangular bars or Charpy V-notch. Also, ensure the specimens are clean and free from surface imperfections. The study used a pendulum-type impact testing machine like a Charpy or Izod impact tester.

Moreover, the machine must be calibrated according to the relevant standards or specifications. Mount the prepared low-carbon steel specimen in the impact testing machine, aligning it correctly. Ensure that the impact surface, such as the V-notch or flat side, is oriented correctly. Raise the pendulum to the specified height, and it will be ready for release. Release the pendulum to swing freely and strike the specimen, generating an impact force. The impact force causes the specimen to deform or fracture, absorbing energy. Note the energy absorbed during the impact, usually measured in joules (J), and record it as the impact toughness [16]. Perform multiple impact tests on different specimens to obtain representative results. Follow the same procedure for each test, ensuring consistency in the test conditions.

2.2.4 Procedure for compressive test

A compressive test procedure is a process for determining the compressive strength of a material, such as metal. The material sample must first be prepared using the specified dimensions and shape according to the required standard or method by beginning the compressive test procedure. For instance, the standard cylindrical specimen measures 110 mm in diameter and 25 mm in length for low-carbon steel. After preparing the sample, it is placed in the testing machine designed to apply a compressive force to the specimen until it fails. At the beginning of the test, the machine is calibrated to identify and confirm its functionality. The machine somehow subjects a load to the specimen at a constant deformation rate between 0. 5 and 2. It is set at zero while the load is constantly recorded during the test. The following is a typical mode of a tensile coupon test carried out on materials: On the other hand, the deformation of the specimen is measured. Thus, the highest load applied on the specimen is divided with the cross-sectional area to give the compressive stress and the material's compressive strength.

2.2.5 Microstructure analysis

Microstructural analysis can be defined as a method of studying the internal structure of materials, including metals, alloys, ceramics and polymers. It involves researching the formation and manner in which the various elements and phases in the material are grouped. The process to follow for microstructural analysis is described as follows. To prepare the metallographic samples, a small strip of steel measuring 10 mm x 10 mm is removed from the more massive piece and is fitted on a metallographic mounting medium using epoxy glue. The sample's surface to be tested is ground and polished to make the surface smooth and shiny like a mirror. The smooth surface of the sample is now treated with a chemical solution to reveal all phases and constituent elements in the steel. The etched sample is then viewed through a microscope, commonly an optical or scanning electron microscope. This makes it possible to visualise and study the microstructure in a further detailed manner.

3. Results

Multiplying engineering characteristics and microstructural research results of metal components are included in this session.

3.1 Output of Testing on Hardness

The experiment on hardness testing for hot rolling was 330 (BHN), and the cold rolling was 349. 01 (BHN), and in the hot rolling, it was seen that cold-rolled samples had higher hardness values than the hot-rolled samples. This can be because of strain hardening, grain structure refinement residual tensions, or work hardening during cold rolling. The hardness of cold-rolled samples is higher than that of hardened samples, which means more hardness, strength, and wear resistance.

The increase and decrease in the hardness of low-carbon steel material are indicated in Figure 4. Knowing the implications of these findings can go a long way in enhancing the practice of process enhancement and materials selection for specific endeavours. The experiment's results need to be analysed about the experiment performed and all the conditions and limitations it encompassed. Also, the experiment's outcome offered the best Brinell hardness number (BHN) of such materials after they were given the hot and cold bends. Applying hot bending to the aluminium frames yielded tests of 245. 26 (BHN) was achieved and was higher than cold bending with 213. 71 (BHN). This is due to coarser grains and the effect of annealing in hot bending, which creates a lower concentration of dislocations. Cold bending produces finer grain structures for the given material and greater dislocation densities, creating greater hardness values [17]. These results are relevant to the trade-off between strength and toughness, choosing appropriate materials for particular use, and controlling bending processes to achieve the required hardness. Last, the experiment estimated materials' hardness (BHN) through hot and cold squeezing.

Consequently, the results observed in the hot squeezing showed a maximum of 231. HOT working investigations revealed that 66 (BHN) encompassed greater hardness values than cold squeezing 221. 09 (BHN); As illustrated in Figure 4, assessment of the effects of both hot and cold working on the hardness characteristic of low-carbon steel. This can be explained by the annealing by dynamic recrystallisation, grain boundary migration, diffusional creep and reduced strain rate in hot squeezing. Such conclusions are essential for expanding the knowledge of the augmentation of strength, the temperature dependence of the squeezing process on the hardness, and the need for material selection and establishing the optimum processes to achieve the desirable hardness levels [18].

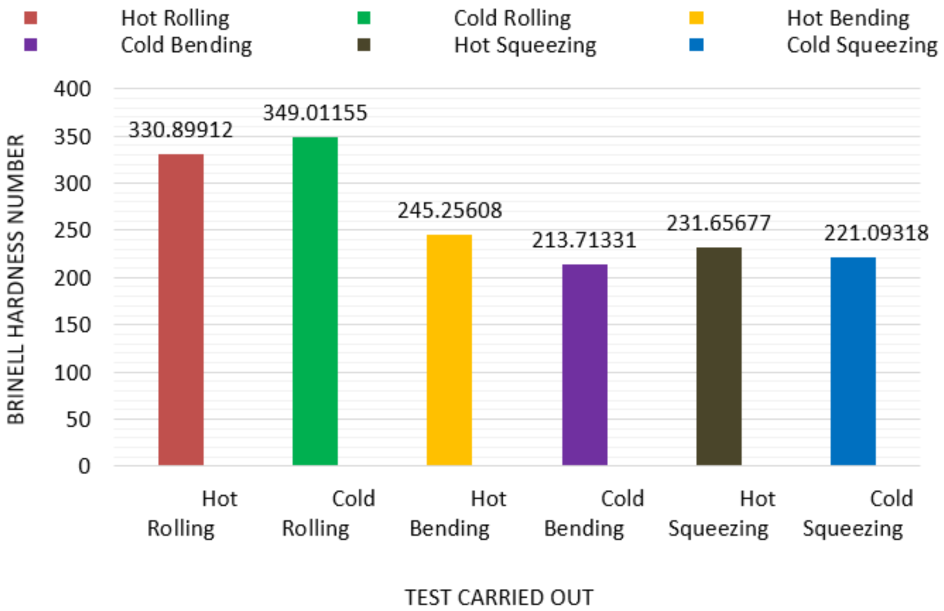


Fig. 4. The effect of hot and cold working on the hardness of low-carbon steel

3.2 Results from the Impact Test

The investigation examined the impact test results for hot and cold squeezing on material hardness (BHN). The results revealed that hot squeezing of 79.14 (BHN) produced higher hardness values than cold squeezing of 54.33 (BHN).

This can be attributed to dynamic recrystallisation, grain refinement, enhanced diffusion, lower dislocation density, and potentially lower strain rates during hot squeezing. In the impact test analysis, the cold rolling process achieved a value of 112.84 (BHN) compared to the hot rolling process with 104.68 (BHN). Furthermore, the hot bending process increases the impact hardness properties by having 60.91 (BHN) compared to the cold bending of 45.51. This results analysis is presented in Figure 5. The impact toughness result from the hardness impact test reveals information about the low-carbon steel's resistance to fracture and deformation under impact loads. A more significant impact toughness rating signifies increased toughness and the ability to absorb more energy prior to fracture [19]. Carbon content, microstructure, heat treatment, and alloying components can all impact low-carbon steel's toughness. Reduced-carbon steel has good impact toughness due to its reduced carbon content, which reduces the chance of brittle fracture. Low carbon steel's impact toughness levels can be compared to industry standards or requirements to determine whether the material is suitable for specific applications. Different applications may demand varying levels of impact toughness, and the hardness impact test findings can assist in assessing whether the low-carbon steel fits the toughness requirements. To summarise, the hardness impact test offers valuable information regarding the impact toughness of low-carbon steel. This test evaluates the material's ability to absorb energy and resist fracture under impact loads, which is critical for applications with dynamic or impact-loading circumstances [20].

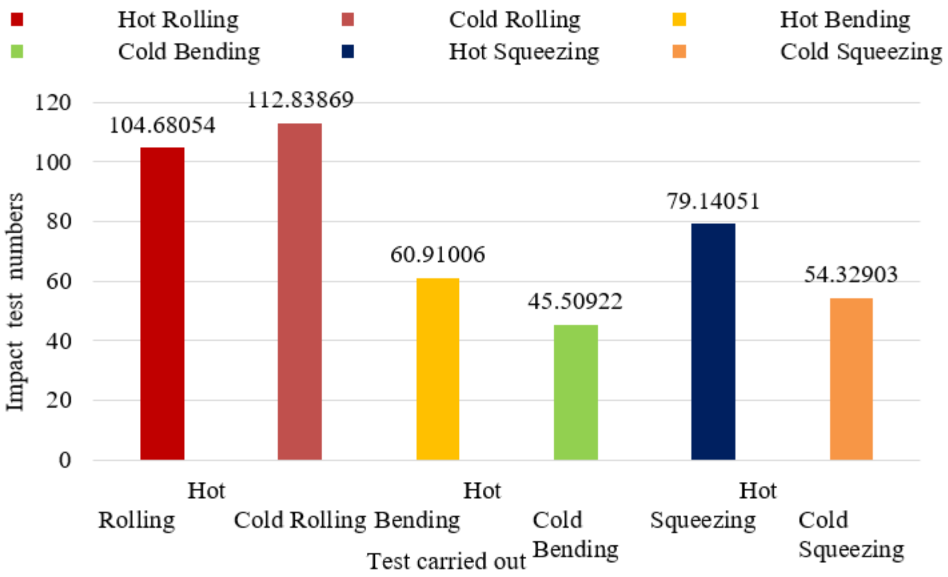


Fig. 5. Impact analysis of the hot and cold effects on low-carbon steel

3.3 Tensile Test Results for Both Hot and Cold Bending

Figure 6 shows how heat and cold working affect low-carbon steel. Hot bending is done at high temperatures, which increases ductility and reduces the risk of cracking. The results demonstrate that the materials are subjected to various loads, including 15385.38 and 16227.49. The most significant tensile stress produces tensile strains of 0.224 (mm) and 0.256 (mm).

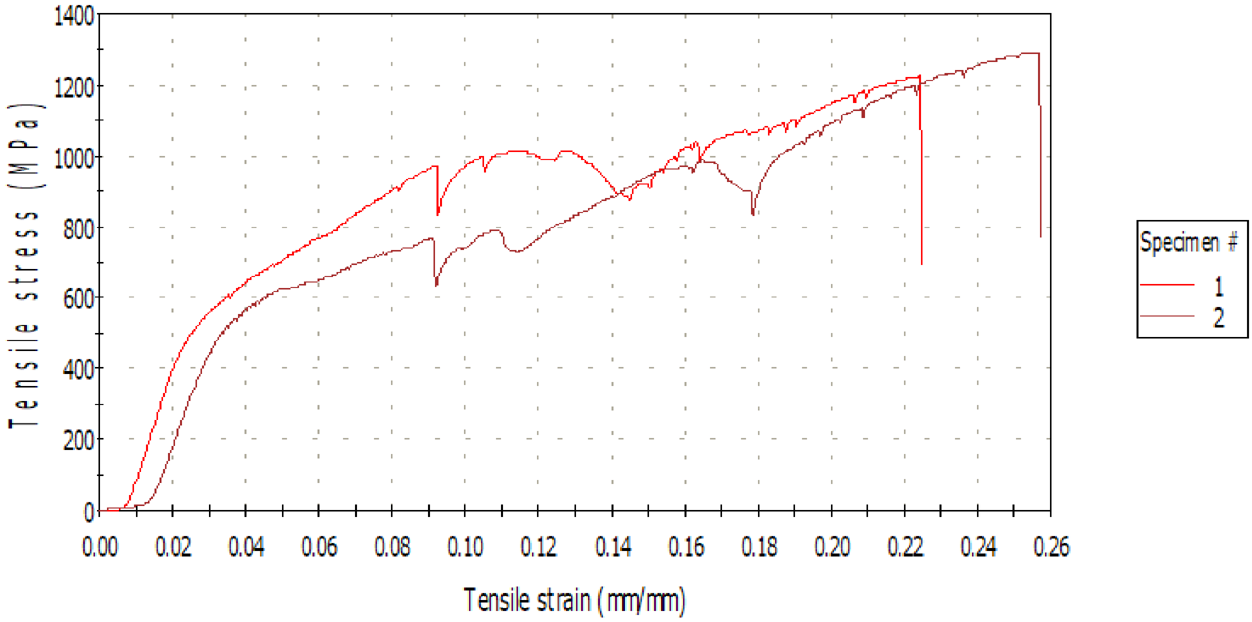


Fig. 6. Low carbon steel: hot bending, cold bending

Thus, the energy consumption is 67.917 (j) and 72.95 (j). Furthermore, cold bending increases energy at maximum tensile stress. Therefore, the tensile stress at its break limit occurs at 1224.06 (MPa) compared with 1289.75 (MPa) for the two operations. The choice between hot bending and cold bending depends on factors such as the desired shape, material properties, and the limitations of the bending process. The specimen parameters used for this experimental work are shown in Table 1, and the analysis of the complete results is depicted in Table 2 and Table 3 for the hot and cold bending processes for sustainable materials manufacturing.

Table 1
Tensile test parameters for low carbon steel: hot bending, cold bending

	Length (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	28.00000	4.00000	1224.32969
2	28.00000	4.00000	1291.34274
Mean	28.00000	4.00000	1257.83622
Standard Deviation	0.00000	0.00000	47.38538

Table 2
Tensile test for low carbon steel: hot bending and cold bending

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	15385.38039	0.22412	6.27525	67.91736	1224.06194
2	16227.49120	0.25596	7.16681	72.94078	1289.75105
Mean	15806.43579	0.24004	6.72103	70.42907	1256.90649
Standard Deviation	595.46227	0.02252	0.63043	3.55210	46.44921

Table 3
Tensile test for low carbon steel: hot bending and cold bending

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)	Modulus (E-modulus) (MPa)
1	15382.015	0.22441	6.28337	68.04235	1014.70264	32251.55029
2	16207.489	0.25685	7.19175	73.34515	792.64453	28175.55847
Mean	15794.752	0.24063	6.73756	70.69375	903.67359	30213.55438
Standard Deviation	583.698	0.02294	0.64232	3.74964	157.01880	2882.16146

In terms of ductility, hot bending increases the material's ductility by reducing its yield strength and increasing its plasticity, facilitating easier deformation. Cold bending relies on the material's strength and elasticity, leading to less ductile behaviour. This result is supported by previous studies [21, 22]. However, hot bending reduces the risk of cracking by improving the material's ductility and reducing residual stresses. In this case, the cold bending carries a higher risk of cracking, especially if the material is strained beyond its ductility limit.

3.4 Result of Tensile Test for Hot Rolling and Cold Rolling on Low Carbon Steel

Figure 7 illustrates the hot and cold rolling impact on the low-carbon steel during the rolling operations. The two primary methods are used for shaping low-carbon steel. Hot rolling involves shaping the steel at elevated temperatures, improving formability, and leading to a refined microstructure. On the other hand, cold rolling is performed at room temperature or slightly below, resulting in strain hardening and increased strength.

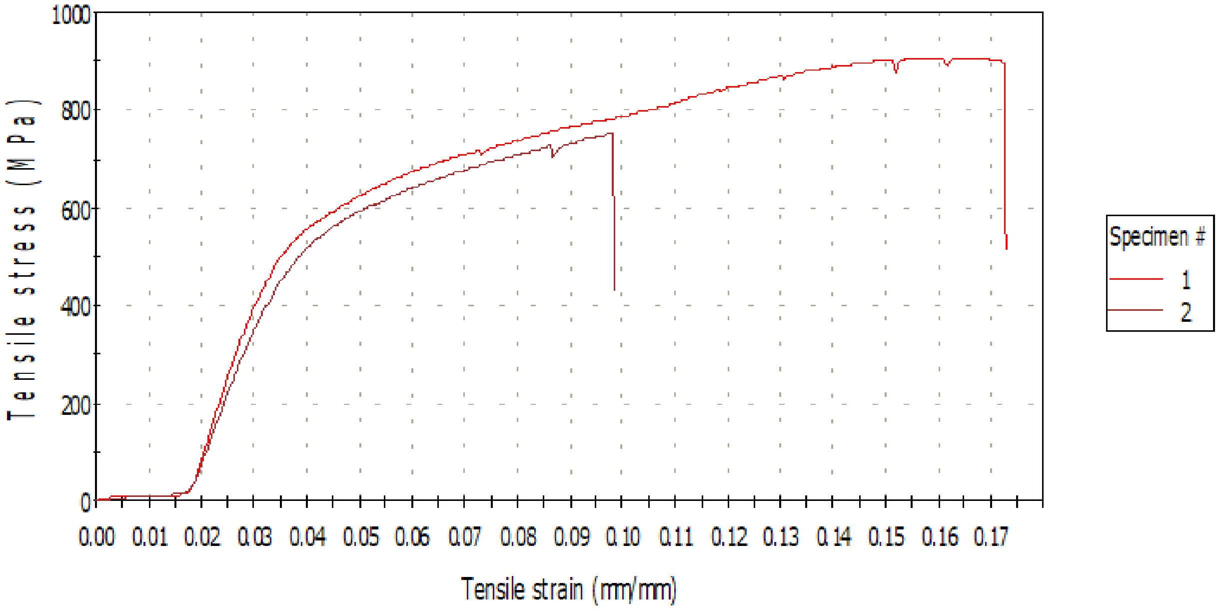


Fig. 7. Low carbon steel: hot rolling, cold rolling

The results show that the low carbon steel could withstand the maximum load of the tensile stress of 11403.32 (N) and 9471.77 (N), respectively, causing the material to have tensile strain at its maximum of 0.1637 (mm) and 0.09822 (mm). The choice between hot and cold rolling depends on the desired product characteristics, required mechanical properties, and the specific application. Understanding the effects of hot and cold rolling on low-carbon steel is crucial for optimising the manufacturing processes and achieving the desired material properties. The deformation parameters are depicted in Table 4. The result analysis is presented in Table 5 and Table 6.

Table 4
Tensile test parameters for low carbon steel: hot rolling, cold rolling

	Length (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	28.00000	4.00000	907.44751
2	28.00000	4.00000	753.73925
Mean	28.00000	4.00000	830.59338

Table 5
Tensile test for low carbon steel: hot and cold rolling

	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	11403.321	0.16370	4.58350	36.74938	896.29052
2	9471.766	0.09822	2.75006	15.97915	753.73925
Mean	10437.544	0.13096	3.66678	26.36427	825.01489
Standard Deviation	1365.815	0.04630	1.29644	14.68677	100.79897

Table 6
Tensile test for low carbon steel: hot and cold rolling

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)	Modulus (E-modulus) (MPa)
1	11263.118	0.17263	4.83356	39.59145	907.44751	31766.0217
2	9471.766	0.09822	2.75006	15.97915	753.73925	27427.636
Mean	10367.442	0.13542	3.79181	27.78530	830.59338	29596.829
Standard Deviation	1266.677	0.05262	1.47326	16.69642	108.68815	3067.7014

3.4 Result of Tensile Test for Hot Squeezing and Cold Squeezing

Figure 8 shows the analysis of hot and cold squeezing, a distinct technique for modifying material through compression. Hot squeezing involves compressing a material at an elevated temperature above 950 C, while cold squeezing involves compression at or below room temperature of 20°C. It can be seen that the hot squeezing techniques have a unique application and significantly improve the mechanical properties and microstructure of the material.

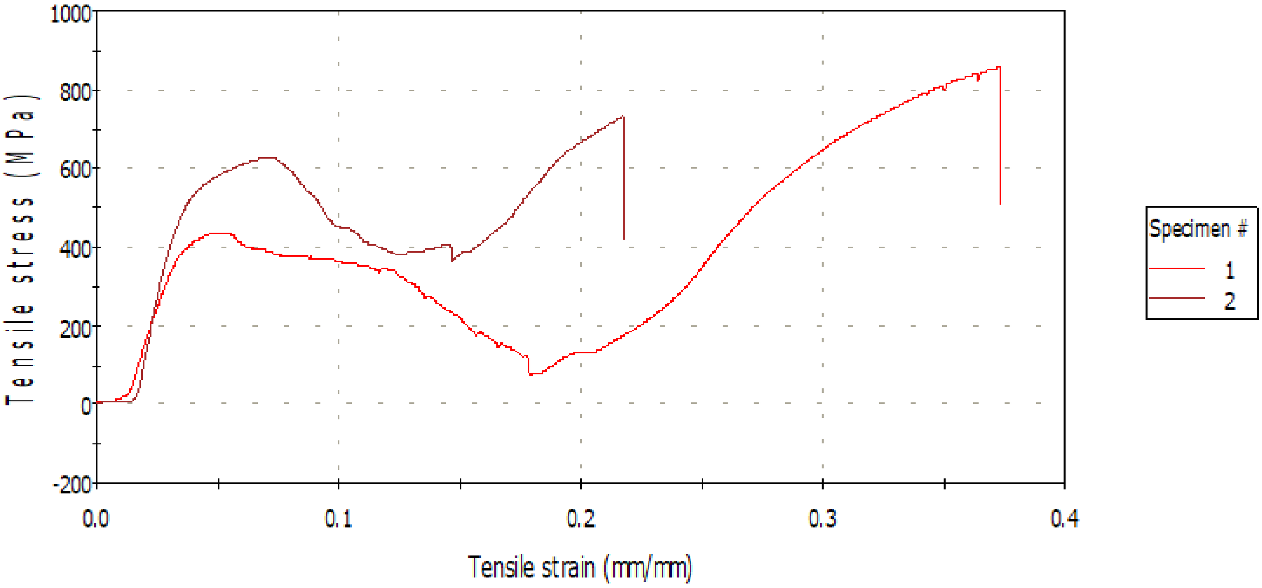


Fig. 8. Low carbon steel: hot squeezing, cold squeezing

The tensile stress at the break for the hot squeezing process is 779.69 MPa compared with the cold squeezing process, having 732.94 MPa. However, the tensile strain shows that hot squeezing has a high strain of 0.373 (mm/mm) compared to cold squeezing of 0,218 mm/mm. Table 7 to Table 9 show the parameters used for the squeezing process and also the results for Modulus (E-modulus) (MPa), Tensile stress at Yield (Zero Slope) (MPa), Energy at Break (Standard) (J), Tensile extension at Maximum Tensile stress (mm), Tensile strain at Break (Standard) (mm/mm), and Load at Break (Standard) (N).

Table 7
Tensile test parameters for low carbon steel: hot squeezing, cold squeezing

	Length (mm)	Diameter (mm)	Maximum Tensile stress (MPa)
1	28.00000	4.00000	857.13006
2	28.00000	4.00000	732.94477
Mean	28.00000	4.00000	795.03741

Table 8
Tensile test for low carbon steel: hot squeezing, cold squeezing

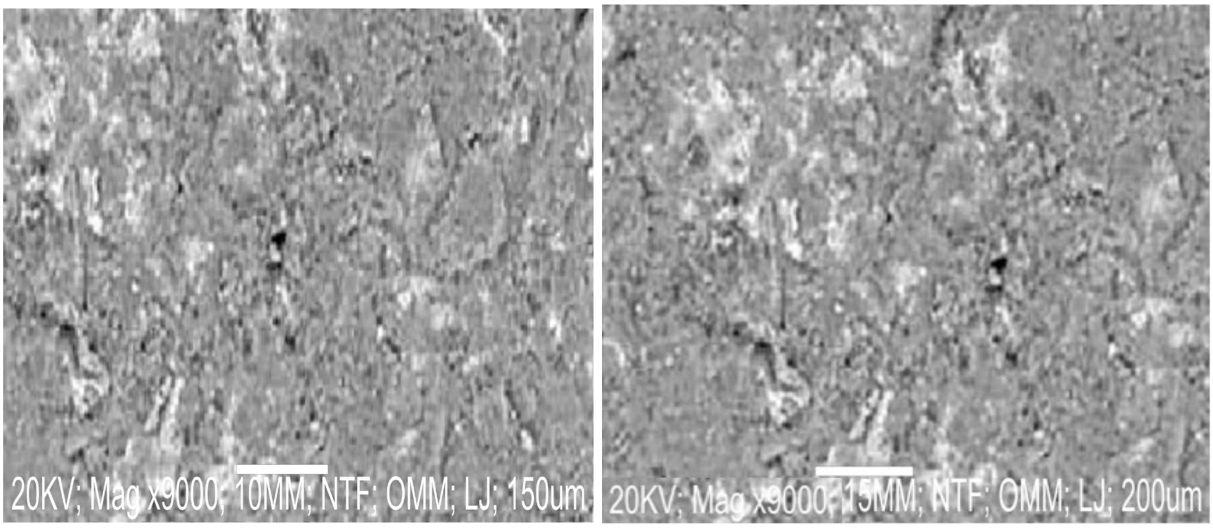
	Load at Maximum Tensile stress (N)	Tensile strain at Maximum Tensile stress (mm/mm)	Tensile extension at Maximum Tensile stress (mm)	Energy at Maximum Tensile stress (J)	Tensile stress at Break (Standard) (MPa)
1	10771.013	0.37322	10.45019	51.26250	779.69178
2	9210.455	0.21785	6.09994	35.31387	732.94477
Mean	9990.734	0.29554	8.27506	43.28818	756.31827
-Standard Deviation	1103.481	0.10986	3.07609	11.27739	33.05513

Table 9
Tensile test for low carbon steel: hot squeezing, cold squeezing

	Load at Break (Standard) (N)	Tensile strain at Break (Standard) (mm/mm)	Tensile extension at Break (Standard) (mm)	Energy at Break (Standard) (J)	Tensile stress at Yield (Zero Slope) (MPa)	Modulus (E-modulus) (MPa)
1	9797.89570	0.37383	10.46719	51.44134	437.82471	18850.43793
2	9210.45542	0.21785	6.09994	35.31387	626.64224	29960.13794
Mean	9504.17556	0.29584	8.28356	43.37760	532.23347	24405.28793
Standard Deviation	415.38301	0.11029	3.08811	11.40384	133.51416	7855.74422

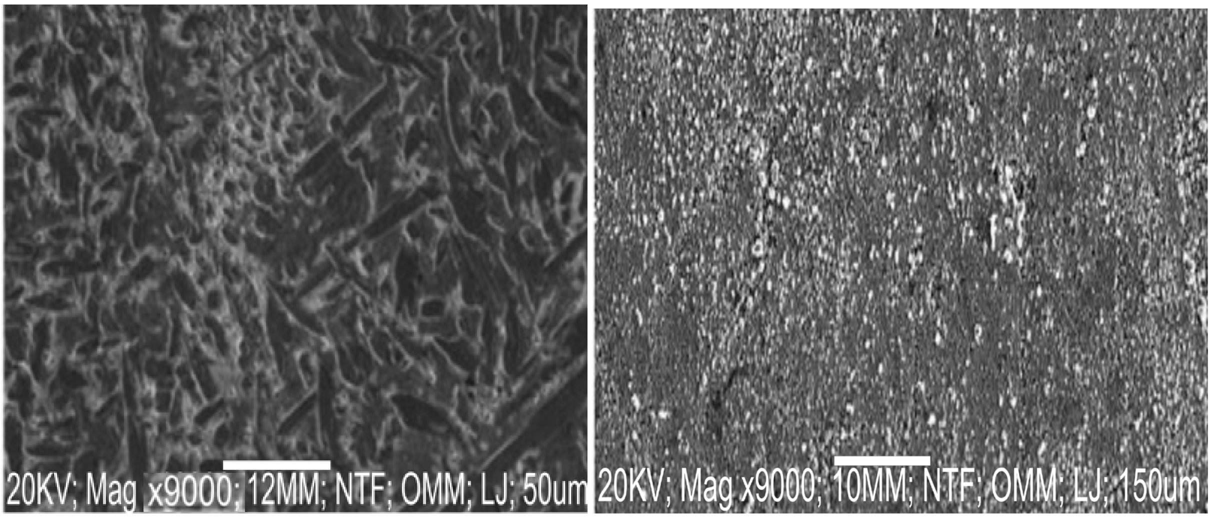
3.5 Microstructural Analysis

Figure 9(a) and Figure 10(a) show that smaller grain sizes formed from the hot rolling are equiaxial grains from hot working. During hot working, recrystallisation causes the creation of smaller grains. The mechanical qualities of the material, such as greater strength, hardness, and fatigue resistance, are often improved by smaller grains. The homogeneity of alloying elements is facilitated by hot working, which leads to a more uniform distribution of the phases [23]. This results in more uniform mechanical characteristics over the whole material. The hot working aids in the reduction of internal tensions and the elimination of dislocations. The steel becomes more ductile and robust due to the heat treatment process. This process will help to form sustainable materials for manufacturing engineering components for industrial use. Figure 9(b) and Figure 10(b) show that the microstructural causes' cold rolling results are considered plastic deformation, leading to strain hardening.



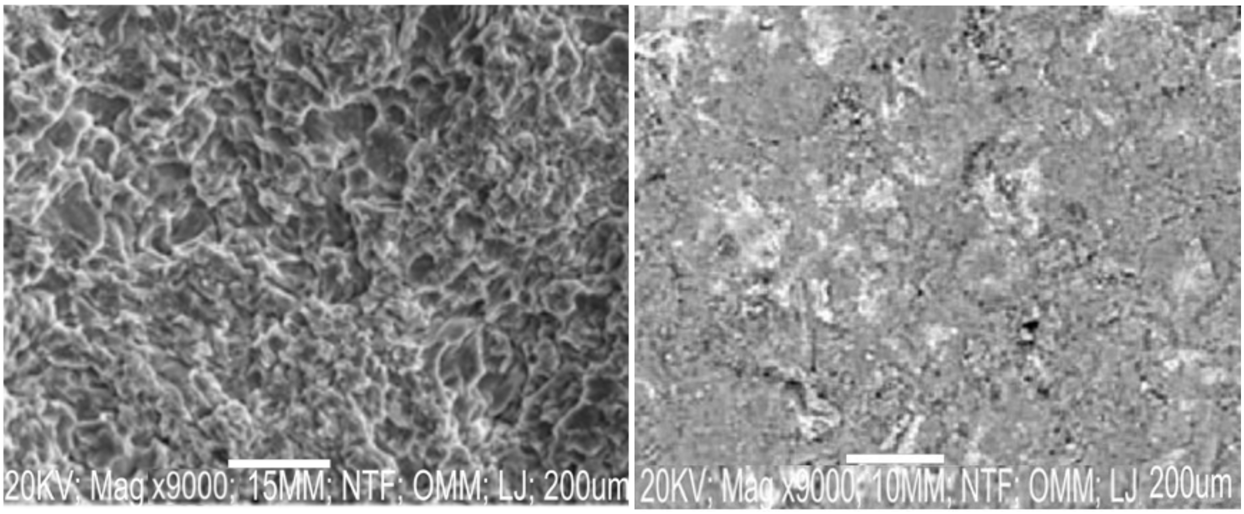
(a) (b)

Fig. 9. The microstructure of the low carbon steel, (a) Hot rolling and (b) Cold rolling



(a) (b)

Fig. 10. The microstructure of low carbon steel (a) Hot squeezing and (b) Cold squeezing



(a) (b)

Fig. 11. Microstructure of the low carbon steel (a) Hot bending and (b) cold bending

The dislocations gather and entangle, increasing the steel's hardness, strength, and yield strength. Cold rolling working lengthens and aligns grain in the applied deformation direction. Due to its preferred grain orientation, a material may have anisotropic mechanical characteristics, meaning that its strength and deformation behaviour vary depending on the direction of deformation. Figure 10(a) and Figure 10(b) depicts the analysis of hot and cold bending of low-carbon steel. Many characteristics of hot-bending steel are lost when hot-bending steel is processed at such high temperatures. During the cold bending process, the materials retained their steel properties. However, much force is needed to bend the low-carbon steel to the desired shape. It becomes more pliable and has a reduced resistance to external forces as a result. This greater flexibility makes it much simpler for hot-bending steel to assume different shapes. Cold bending can result in the development of deformation twins, which may impact the material's mechanical characteristics. Twins influence critical mechanical properties in steel, such as strength, ductility, and deformation processes. Therefore, it can be concluded that cold working leads to strain hardening. The material properties essential for a given application determine which of these two forms of working is optimal: if the combination of properties is close to the ideal for the material's application, hot working is chosen; otherwise, cold working is preferable which is in line with the previous studies of [24-27]. Heat bending also aids in increasing the rate of recrystallisation and grain refinement; hence, finer grain size and dislocation density are reduced; this improves the mechanical properties because the smaller the grain sizes of the low-carbon steel, the better the mechanical properties. Cold bending results in strain hardening that raises the dislocation density and possibly the strength and hardness.

4. Conclusions

Low-carbon steel is not immune to hot and cold working effects. Therefore, the effects of hot and cold working have been discussed and analysed in this paper. Hot working is the ability to deform the steel by heating, while cold working is deforming steel without heating. In both hot and cold chemical procedures, the alteration of microstructure, mechanical properties, and performance of low-carbon steel is greatly affected. The hot and cold working investigation emphasised those working parameters, such as rolling, squeezing, and bending, on low-carbon steel's mechanical and microstructures. This work has the following conclusion:

i. The study shows that the Brinell hardness increases during the cold rolling process, having 349.011 BHN, compared to the hot rolling process, which has 330.89 BHN. Furthermore, the hot bending process increases the hardness properties compared to cold bending, having 245.25 and 213.71 BHN, respectively. Also, the study shows that the squeezing process of the hot is 231.65, as opposed to 221.09 BHN of the cold squeezing process.
ii. The impact test results show that the cold rolling process has a higher impact on the materials of the low-carbon steel than the hot rolling process, such as 112.84 for cold rolling and 104.68 for the hot rolling process. Also, when it comes to the bending process, low-carbon steel exhibits a higher impact than cold bending, having 60.91 and 45.51, respectively.
iii. The hot rolling process reduces the grain sizes, which assists in a sustainable homogeneity of the low-carbon steel, increasing the working sample's hardness and impact properties.
iv. The hot rolling process possesses the 11263.11 (N) load at the break for the tensile test, which is higher than the cold rolling, having 9471.7 (N). This also goes the same way as the elastic modulus having 31766.02 (MPa) and 27427.64 (MPa). Furthermore, the hot rolling process increases the tensile stress at a zero slope of low carbon steel, having

907.45 (MPa) against 753.74 (MPa) for the cold rolling process. Also, the tensile train increases in the hot rolling process in contrast with the cold rolling.

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