

# Effects of Alloying Element and Heat Treatment on Mechanical Properties of Alloy Steels

Umma Abdullahi



Received: 29 March 2023  
Accepted: 08 June 2023  
Published: 01 July 2023  
Publisher: Deer Hill Publications  
© 2023 The Author(s)  
Creative Commons: CC BY 4.0

## ABSTRACT

The effects of Cr and Ni on three different types of steel with different carbon ratios under constant conditions such as the welding current 120A, voltage 80V, Diameter 10 mm and angle 60 degree was observed. Nickel percentage of up to 0.147% and Chromium 0.083% contributed to affecting the mechanical properties of the steel. Undissolved carbide particles refine the austenite grain size. In the presence of nickel, chromium carbide is less effective in austenite grain refinement than chromium carbide in absence of nickel at temperature below 975°C. Nickel does not produce any austenite grain refinement but presence of nickel promotes the formation of acicular ferrites. It was also found that Ni and Cr as chromium carbide also refines the ferrite grain size and morphology. Cr as chromium carbide is more effective in refining ferrite grain size than nickel. The microstructure of the base metal as a reference material was analysed before heating to support the results of chemical analysis. Nickel percentage of up to 0.147% and Chromium 0.083%. Molybdenum was 0.03% which contributed to affecting the mechanical properties of the steel.

**Keyword:** Alloy steel, Heat treatment, Chromium, Nickel, Grain size

## 1 INTRODUCTION

With the technological development in advanced industries such as oil, automotive, aviation, piping networks, metallic bridges and other important industries, the need for a steel with higher tensile strength, adequate ductility and toughness has increased (Razzak M.A, 2011; Abdullahi U, 2022; Bello et al., 2021). This has been principally the issue at hand where light weight is needed, as in the automobile and aircraft industries. An increase in carbon content met this demand in a limited way, but even in the heat-treated condition the maximum strength is about 600-700 MPa above which value, a rapid decrease in ductility and impact strength arises and large effects limit the permissible section (Ragu et al., 2015). Heat treated alloy steels provide high strength, high yield point, combined with significant ductility even in large sections. The use of plain carbon steels frequently necessitates water quenching accompanied by the danger of distortion and cracking, and only thin section can be hardened throughout. For resisting corrosion and oxidation at elevated temperatures, alloy steels are essential. The researchers in this area assumed the following definition: 'Carbon steels are regarded as steels containing not more than 0.5% manganese and 0.5% silicon, all other steels being regarded as alloy steels' (Material handbook, 1964). The major alloying elements added to steel in generally varying amounts either separately or in compound mixtures are nickel, chromium, manganese, molybdenum, vanadium, niobium, silicon and cobalt. The observation in this paper is directed towards experiment on low alloy steels (0.095-0.99 wt% C) which has a high weldability and toughness. These properties are in high priority for structural steel if these can be blended in with a high tensile strength. The sole purpose of this study is to find out proper alloying elements to increase the tensile properties with appropriate heat treatment. In the current study three different steels including plain carbon (PC) steel with varying weight percentages of Ni and Cr were used to observe the effects of alloying elements. The effects were characterized according to the presence of alloying elements either alone or in combination with each other in the low carbon steel samples. The steel samples were characterized using mechanical testing method. Tensile strength and elongation data were collected to compare the effects of heat treatment and alloying elements. Metallographic analysis was also done to confirm a correlation between alloying elements and microstructural feature like grain size and morphology.

## 2 EXPERIMENTAL WORK

### 2.1 Specimen Preparation

Three different steels containing the range of 0.095%-0.99% carbon and plain carbon steel were used in this study. The composition of the steels was presented in Table 1, 2 & 3 for low, medium and high carbon steel respectively.

---

U. Abdullahi ✉  
Mechanical Engineering Department, Faculty of Engineering  
Bayero University, Kano, PMB 3011 Kano State Nigeria  
E-mail: ummaabdullahi@abu.edu.ng

Reference: Abdullahi (2023). Effects of Alloying Element and Heat Treatment on Mechanical Properties of Alloy Steels. International Journal of Engineering Materials and Manufacture, 8(3), 67-74.

The steels were heat treated in an air induction furnace. About 15 mm diameter specimens of each steel were rolled down in order to study the austenite grain coarsening behaviour.

## 2.2 Carburization and Measurement of Austenite Grain Size

Considering the size of the austenite grains as it directly affects the succeeding structure and hence the properties of steels, a study was made to determine prior austenite grain size at temperatures higher than upper critical temperature. Carburization technique was deployed to deduce prior austenite grain size. There are also other methods in determining prior austenite grain size like isothermal transformation technique, oxidation technique, etc. But previous work showed that the isothermal technique did not work well in revealing prior austenite grain boundary of low alloy steels (Razzak, 2011; Ragu et al., 2015; Clark & Varney, 1962). Therefore, carburization technique was implemented to reveal prior austenite grain boundaries of steels in this work. The technique is based on the formation of a continuous cementite network at the austenite grain boundaries. Carbon will diffuse in steel from the carburizing atmosphere forming hypereutectoid steel at the surface of the specimen and during slow cooling in the furnace continuous cementite network is formed at the austenite grain boundaries at the selected austenitizing temperatures. Subsequent etching of the furnace cooled samples revealed the cementite network formed which marked the prior austenite grain size at the selected carburizing temperatures (Clark & Varney, 1962; Erding et al., 2019). Solid carburizing or pack carburizing technique was used for this research. The steel specimens were heated to different austenitizing temperatures, i.e., 900–1050°C with an interval of 50°C. Before heating these specimens, they were packed in a pot with carburizing mixture. Then they were placed in a dedicated furnace. Subsequently, when reaching the required temperature, they were held at that temperature for 2 h to reach near the equilibrium condition and then cooled in this furnace to room temperature. Slow cooling ensured a continuous cementite network through the austenite grain boundaries. The assessment of prior austenite grain size was made from direct measurement of the austenite grains in the specimens under optical microscope. The grain size was measured using the mean linear intercept method, counting grain boundary intersections with the circumference of the circle in the eyepiece of a microscope. The effective circumference of the circle was determined precisely by measuring its diameters with reference to a stage  $\mu\text{m}$  at the magnification used. A total of at least 300–600 intersections were counted for each specimen. Then the size of austenite grain was measured using the mean linear method.

## 2.3 Mechanical Testing

The heat treated 13 mm diameter bar was then machined into standard tensile specimens with a nominal diameter and gauge length of 3.99 and 25 mm respectively. The grip size was chosen to be 13 mm in width and in length as shown in figure 1. The tensile specimens were then tested with a Universal Tensile Testing Machine (INSTRON) to obtain data on yield strength (YS), ultimate tensile strength (UTS), percentage of elongation (% EL), and percentage of reduction in area (% RA).

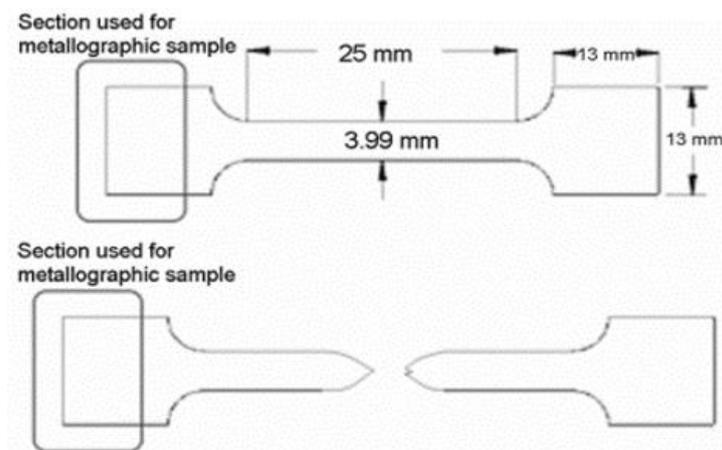


Figure 1: Dimensions of tensile specimen and location on sample for subsequent microstructure study

## 2.4 Optical Microscopy

Samples from fractured tensile specimens were taken for microscopic examination. To avoid heavily deformed zone for microstructure observation, samples were chosen from the grip of the tensile test specimen as shown in Figure 1. The samples were then ground, polished up to  $\gamma$ -aluminium powder and then etched in 5% Nital solution. The microstructure of these specimens was then studied. Optical microscope photograph (Figure 4) of the microstructure of each specimen was taken to compare the microstructural features in conjunction with the mechanical properties.

### 3 EXPERIMENTAL RESULTS

#### 3.1 Alloying Elements

Three different types of alloy steel were used in this work as low, medium and high carbon steel. The classification was based on the carbon content, but according to the level of main mechanical properties of practical importance. As Low Carbon Steels having carbon up to 0.25%, Medium Carbon Steels having carbon between 0.25% to 0.55% and High Carbon Steels has carbon from 0.55% to ideally a maximum of 2.11% but commonly up to 1.5% max. in commercial steels. And this is the most commonly used commercial classification. Table 1, 2 and 3 present the result of chemical composition of the three selected carbon steel.

**Table 1:** Chemical composition of low carbon alloy steel

C	Si	Mn	P	S	Cr	Ni	Mo	Al
%	%	%	%	%	%	%	%	%
0.095	0.235	0.90	0.011	0.013	0.0083	0.147	0.030	0.039
Cu	Co	Ti	Nb	V	W	Pb	Mg	B
%	%	%	%	%	%	%	%	%
0.208	0.019	≤ 0.0010	≤ 0.0040	≤0.0010	≤0.010	≤0.0030	≤0.0010	0.0008
Sn	Zn	As	Bi	Ca	Ce	Zr	La	Fe
%	%	%	%	%	%	%	%	%
0.012	≤0.0020	0.020	≤0.0020	0.00003	≤0.0030	≤0.0015	≤0.0010	98.2

**Table 2:** Chemical composition of medium carbon alloy steel

C	Si	Mn	P	S	Cr	Ni	Mo	Al
%	%	%	%	%	%	%	%	%
0.272	0.108	0.449	0.00089	0.014	0.0027	0.029	≤ 0.0020	0.042
Cu	Co	Ti	Nb	V	W	Pb	Mg	B
%	%	%	%	%	%	%	%	%
0.016	0.013	≤ 0.0010	≤ 0.0040	≤0.0010	≤0.010	≤0.0030	≤0.0010	≤0.0005
Sn	Zn	As	Bi	Ca	Ce	Zr	La	Fe
%	%	%	%	%	%	%	%	%
≤0.010	≤0.0020	≤0.0010	0.0046	0.011	0.0051	≤0.0015	0.0017	99.0

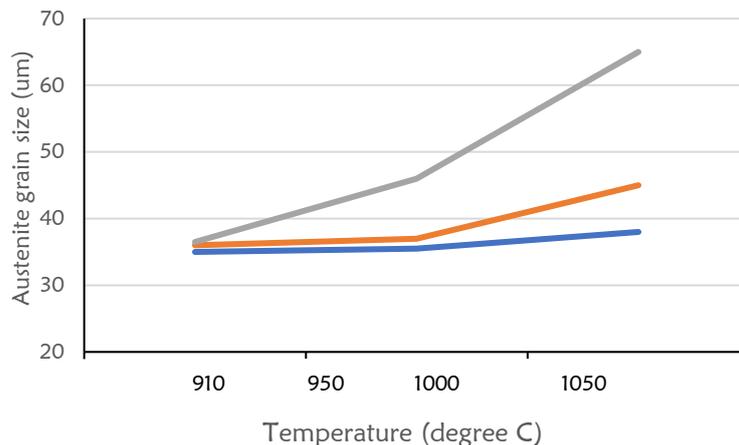
**Table 3:** Chemical composition of high carbon alloy steel

C	Si	Mn	P	S	Cr	Ni	Mo	Al
%	%	%	%	%	%	%	%	%
0.99	0.407	0.79	0.046	0.227	0.127	0.132	0.049	0.127
Cu	Co	Ti	Nb	V	W	Pb	Mg	B
%	%	%	%	%	%	%	%	%
0.065	0.050	0.014	0.023	0.0023	0.414	0.132	0.175	0.028
Sn	Zn	As	Bi	Ca	Ce	Zr	La	Fe
%	%	%	%	%	%	%	%	%
0.022	≥ 0.036	0.036	0.0048	≥ 0.015	0.180	≤ 0.0015	-0.261	≤ 94.6

#### 3.2 Austenite Grain Size

The heat-treatment temperatures of steels were determined by a careful examination of the austenite grain size. The criteria for the determination of the heat treatment temperature of steels were that the steel had the same austenite grain size and that the temperatures were such that an appreciable proportion of the solute elements had entered into solution for subsequent precipitation. This is indicated in figure 2 by a steep rise of the austenite grain size. An austenite grain size of 38 μm was found to be suitable and the corresponding heat-treatment temperatures for the steels were 910, 900, 970 and 950°C for the steels 1–3, respectively. The dissolution temperatures obtained by the equilibrium thermodynamic calculation is below the one expected from the experimental one. As heat treatments were done for 2 h at higher temperatures, it is logical to expect that the precipitating elements will be completely in solution at the chosen heat treatment temperature.

The prior austenite grain size against temperature graph is plotted and shown in figure 2. The figure shows that, the austenite grain size increases with increasing austenitizing temperature. For steels 1 and 2 this relation is almost linear. Steel 1 is a low carbon steel and it does not contain higher number of alloying elements especially carbon. Hence, there is no obstruction for grain growth and the austenite grain size increases rapidly and linearly with temperature. Steel 2 is basically medium carbon steel with nickel in a little higher percentage than in steel 1. This steel also showed similar austenite grain coarsening behaviour as that of low carbon steel 1. Nickel remained in solid solution and not combined with carbon to produce any second phase particles. In absence of second phase particles in steel 2, grain growth is not hindered. Steel 3 produced the finer austenite grain size than steel 1. Cr combines with carbon and forms chromium carbide precipitates (Ragu et al., 2015; Clark & Varney, 1962; Erding et al., 2019; Armentani, 2007; Kang et al., 2007).



**Figure 2:** Variation of prior austenite grain size with temperatures for steels 1-3

These precipitates pin the austenite grain boundaries and inhibit grain growth resulting in finer austenite grain size than steel 1. Steel 3 also produced grain size finer than steel 1 and coarser than steel 2 (Ragu et al., 2015; Clark & Varney, 1962; Kang et al., 2007; Jeshvaghani & Mirzaei, 2013).

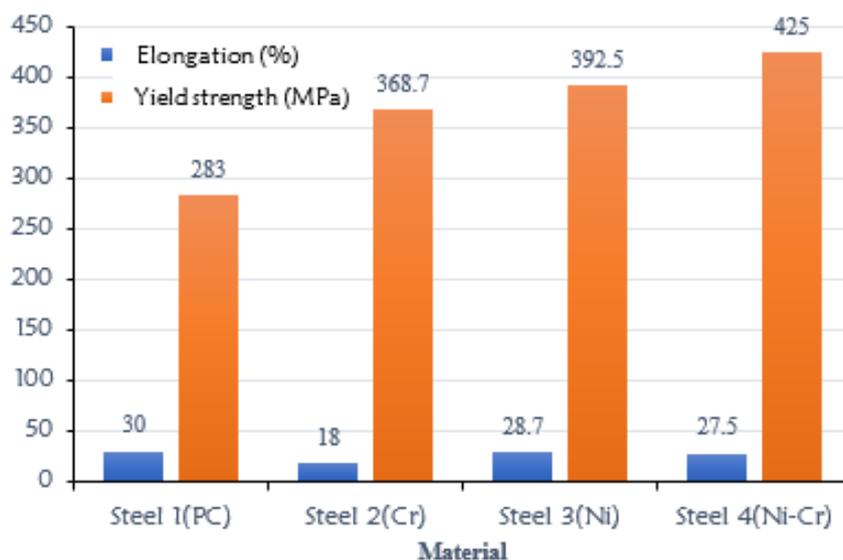
Steel 3 contains both Cr and Ni in a little higher percentage than the two steels. As it was observed from steel 1 nickel does not have much significant effect on the austenite grain refinement. Therefore, the finer austenite grain size in steel 3 compared to steel 1 is clearly due to the effect of chromium carbide precipitates. The austenite grain size of steel 2 remains finer up to 950°C beyond this temperature; there is a steep rise in austenite grain growth. Steel 2 produced finer grain size than steel 3 with (Ni + Cr) up to a temperature of 975°C and above this temperature steel 3 produced finer austenite grain size than steel 2. Composition of steel suggested that steel 2 (Cr = 0.0027 wt.%) should contain slightly higher volume fraction of precipitates than steel 3 (Cr = 0.127 wt.%). Presence of higher volume fraction of precipitates increased the grain boundary pinning (Zener pinning) efficiency and thus results in smaller grain size as observed from figure 5 showing the prior austenite grain boundaries of steels 1–4 revealed by carburization technique at 1000°C ( $\times 200$ ).

The results also indicate that, presence of nickel, chromium carbide is less effective in austenite grain refinement than chromium carbide in absence of nickel at temperature up to 975°C. Moreover, presence of nickel decreases the chromium carbide dissolution temperature in the low alloy steels. Among the three alloys, steel 2 showed the same grain coarsening behaviour as steel 1. This confirms the previous understanding that Ni has no effect on the austenite grain size refinement. Finer austenite grain size of steels 2 and 3 indicated that Cr as chromium carbide is an effective grain refining element for HSLA.

### 3.3 Mechanical Properties

Presence of acicular ferrite effects the mechanical property by lowering elongation and increasing yield strength (Clark & Varney, 1962; Frost, 1991; Panel et al., 2022; Boumerzoug et al., 2011). In the case of steel 4 with higher amount of Ni and Cr as alloying elements did not show any significant changes in ferrite morphology, thus the elongation obtained is equal to the base steel 1. It can be expected that the presence of second phase particles and smaller grain size in steels 3 and 4 should yield less elongation which is contradictory with the experimental results obtained. The explanation can be given from the point of view of the fraction of pearlite present in the microstructure and its distribution. Presence of second phase particle decreased the amount of carbon available in the matrix. Smaller weight fraction of carbon available during cooling should yield lower fraction of pearlite in the microstructure in comparison with the base plain carbon steels 1 and 2 (Ni). Lower volume fraction of pearlite in the microstructure in conjunction with finer distribution increased the deformability in steels 3 and 4. The effects of second phase particles and smaller ferrite grains in decreasing ductility is somewhat countered by the effects of change in distribution and lower fraction of pearlite in the microstructure in increasing ductility.

Figure 3 shows the tensile test results from the specimens of steels 1–4 cooled at 120°C/min. It is evident from the figure that yield strength of steels 2–4 is higher than the base steel 1 (PC). Among the three alloy steels, steel 4 with Ni and Cr produced the highest yield strength and steel 2 with Ni produced the lowest yield strength. Steel 3 with chromium produced yield strength in between steels 2 and 4. A similar trend was found with the ultimate tensile strength of these steels. The higher yield strength of steel 3 with Cr than steel 2 with Ni indicated that Cr is more effective than nickel in increasing yield strength. The highest yield strength of steel 4 with Ni and Cr is clearly due to the combined effects of Ni and Cr. Nickel does not produce any second phase particle.



**Figure 3:** Comparison of yield strength and elongation of steels 1–4 cooled at 120°C/min

Ni is found mostly in the form of solid solution in the ferrite (Clark & Varney, 1962; Kang et al., 2007; Jesvaghani & Mirzaei, 2013; Hastuhiko et al., 2007). However, Ni increased the strength of the steel by solid solution strengthening. Besides that, Ni also lowers the transformation temperature, even though the lower transformation temperature produces smaller ferrite grains (Clark & Varney, 1962; Kang et al., 2007; Jesvaghani & Mirzaei, 2013). Besides that, it was observed from the microstructural observation, presence of Ni promotes acicular ferrite formation. Change in morphology of the ferrite to acicular ones also produces obstacle in dislocation glide. Thus, nickel increases the strength by refining the grains by lowering the transformation temperature and also changing the morphology of the ferrite grains.

Chromium in the form of chromium carbide precipitates increased the strength by means of precipitation strengthening. Secondary chromium carbides pin the grain boundaries and inhibit the grain growth. This results in grain refinement and presence of second phase particles also makes dislocation movement more difficult. Second phase particles like chromium carbide in the matrix increases the energy required for elastic/plastic deformation, hence creates higher strength in the alloy. Percentage of elongation in steels 1, 3 and 4 showed similar results while steel 2 with Ni in solid solution showed reduced elongation.

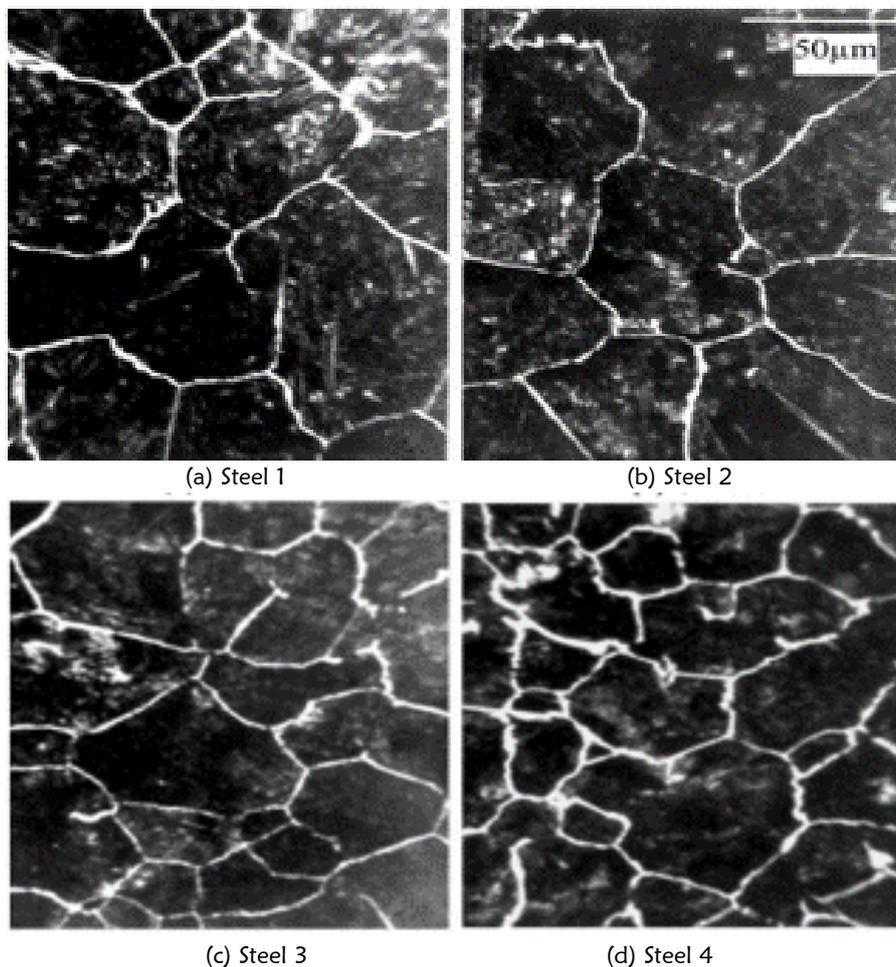
### 3.4 Morphology of Steel

It was observed that steels 1–4 showed regular ferrite–pearlite structure with some ferrite morphology change in steel 2. The microstructure observed comprised of fine ferrite–pearlite structure where the pearlite is isolated in the ferritic matrix. Steel 2 at the fast-cooling rate of 120°C/min showed some widmanstatten ferrite along with regular ferrite pearlite. Steels 2–4 produced finer ferrite pearlite than steel 1. Among the three alloys, steel 3 produced finer grain size than steel 2 and steel 4 produced the finest grain structure of all steels as noticed also in figure 5. Microstructural observation showed presence of acicular ferrite in steel 2. The microstructures of steels 1–4 cooled at 120°C/min are shown in figure 6. Steel 2 has Ni as alloying elements; hence it showed smaller grains in comparison with the plain carbon steel 1. It is well known that Ni lowers the austenite to ferrite transformation temperature and thus produced condition for smaller ferritic grains to nucleate at relatively low grain mobility condition. Besides that, from the microstructural observation shown in figure 6 it was also clear that Ni modified the ferrite morphology to more acicular shape. Steel 3 contains a little higher amount of Cr than steel 2. And Cr combines with C and formed chromium carbide precipitates during cooling from the austenite zone.

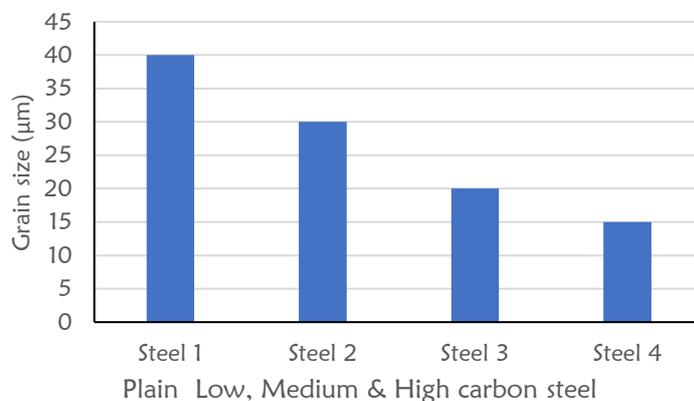
These chromium carbide precipitates pin the newly nucleated ferrite grain boundaries and thus fine ferrite grain is obtained. The finer grain size of steel 3 than steel 2 clearly indicate that Cr as chromium carbide is more effective in ferrite grain size refinement than nickel. Steel 4 contains both Ni and Cr. The finest ferrite grain size of this steel is

due to the combined effects of nickel and chromium. However, it can be said that Cr in presence of Ni is more effective in producing finer microstructure. In figure 6, average grain diameter of steels 1–4 is presented. Grain size measurement also suggested the same phenomenon predicted by microstructural observations. Considering the experimental error, it can be said that steel 4 has the smallest mean grain diameter of  $\sim 15 \mu\text{m}$ .

Steel 2 showed smaller grain diameter than steel 1 but it should be considered that acicular morphology of ferrite in the microstructure of steel 2 produced greater extent of error in the measurement by mean linear intercept method. So, ferrite grain size measurement for steel 2 is not fully reliable.



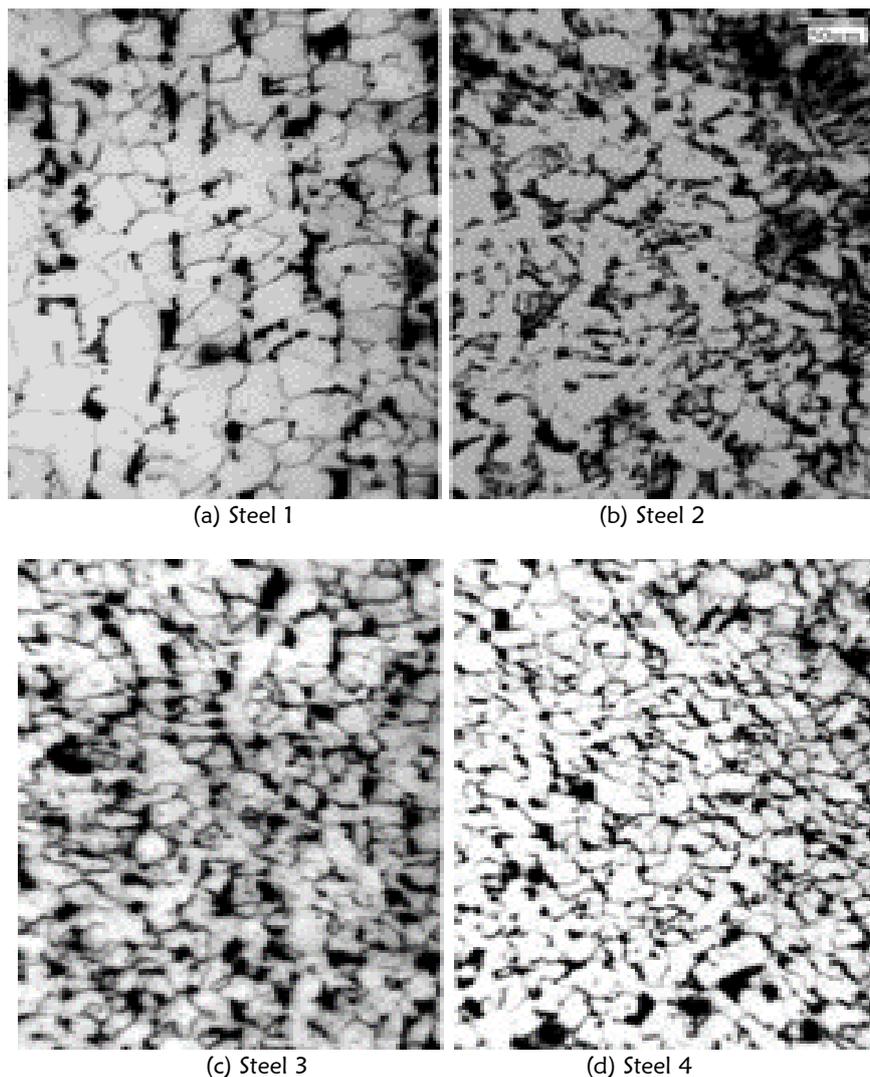
**Figure 4:** Optical micrograph showing prior austenite grain boundaries of steels 1–4 revealed by carburization technique at  $1000^{\circ}\text{C}$  ( $\times 200$ ).



**Figure 5:** Average grain diameter of steels 1–4.

#### 4 CONCLUSIONS

The carburization method is a practically suitable technique in deducing the prior austenite grain boundaries in low carbon steels comprising nickel and chromium as alloying elements. On heating undissolved particles of chromium carbide refined the austenite grain size. In the presence of nickel, chromium carbide is less effective in austenite grain refinement than chromium carbide in absence of nickel at temperature below 975°C and the reverse is true above 975°C. Nickel did not produce any austenite grain refinement. Nickel and chromium as chromium carbide precipitates were found to refine the ferrite grain size. Cr is found to be more effective in the refinement of ferrite grain size than nickel. Nickel in solution and chromium as chromium carbide precipitates increased the yield strength of the low carbon steels but the effectivity of chromium carbide precipitates in the increment of yield strength was found to be more than that of nickel. In the presence of nickel, the contribution of chromium carbide.



**Figure 6:** Optical micrograph of steels 1–4 cooled at 120°C/min ( $\times 200$ ).

#### ACKNOWLEDGEMENT

The author acknowledged the support from TETFund IBR 2021 intervention through Ahmadu Bello University, Zaria and also appreciated the University for providing all the equipment used to conduct the research.

**REFERENCES**

1. Abdullahi, U. (2022). Effect of Tempering Treatment on the Post-Weld Properties and Chemical Compositions of ArcWelded Alloy Steels. *International Journal of Engineering Materials and Manufacture*, 7(4), 89-94
2. American Society for Metals 1964 Metal handbook (Materials Park, Ohio: American Society for Metals) 8th edn, Vol. 2
3. Armentani, E. R. (2007). The effect of thermal properties and weld efficiency on residual stresses in welding. *Journal of Achievements in Materials and Manufacturing Engineering*, 20, No. 1-2, 319-322.
4. Bello K. A., Abdullahi U., Adeniyi A.S, Adebisi A. A, Dodo R. M., Abdulwahab M., Adekunle A.S, (2021). Optimizing Tensile Properties of Age Hardened A356 Aluminium Alloy via Taguchi Method. *Nigerian Journal of Engineering*, 28(1), 61-68
5. Boumerzoug, Z., Raouache, E., Delaunois, F. (2011). Thermal cycle simulation of welding process in low carbon steel. *Materials Science and Engineering: A*, 530, 191-195.
6. Clark D S and Varney W R 1962 *Physical metallurgy for engineers* (New York: Litton Educational Publishing Inc.) 2nd edn
7. Erding W., Renbo S.\* and Wenming X., (2019). Effect of Tempering Temperature on Microstructures and Wear Behavior of a 500 HB Grade Wear-Resistant Steel. *Metals* 2019, 9, 45
8. Frost N.E., dugdale D.E, (1991). The propagation of fatigue cracks in sheet specimens. *Journal of Sound & Vibration*, 69, No. 4.
9. Hamid M. M., Effect of Heat Treatments on the Mechanical Properties of Welded Joints of Alloy Steel by Arc Welding. *Diyala Diyala Journal of Engineering Sciences* Vol. 12, No. 02, June 2019, pages 44-53
10. Hastuhiko. O, Tatsuya. S, Tadashi, (2007). Weld ability of High Strength Steel, (HSS) Sheets for Automobiles, *Nippon Steel Technical*, No.95.
11. Jeshvaghani, R.A and Mirzaei,R ,M ,(2013). Study of welding velocity and pulse frequency on microstructure and mechanical properties of pulsed gas metal arc welded high strength low alloy steel. *Materials & Design*, 51, 709-713.
12. Kang J S, Huang Y, Lee C W and Park C G 2007 *Adv. Mater. Res.* 15–17 786
13. Panel X. W., Changbo L., Yuman Q., Yanguo L., Zhinan Y., Xiaoyan L., Mingming W. and Fucheng Z., (2022). Effect of tempering temperature on microstructure and mechanical properties of nanostructured bainitic steel. *Material Science and Engineering: A*, 832.
14. Ragu N. S., Balasubramanian V., Malarvizhi S., Rao A.G., (2015). Effect of welding processes on mechanical and microstructural characteristics of high strength low alloy naval grade steel joints. *Defence Technology* 11, 308-317
15. Razzak, M. A. (2011). Heat Treatment and Effects of Cr and Ni in Low Alloy Steel. *Bulletin of Materials Science*, 34, 1439-1445.