



BENHA UNIVERSITY
FACULTY OF ENGINEERING SHOUBRA
DEPARTMENT OF MECHANICAL ENGINEERING

A Thesis submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science

"SOME INVESTIGATIONS ON LOW TEMPERATURE CAST CARBON STEEL"

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Summary

Steel is the most common alloy used in different applications due to the great variety of properties it can possess. Carbon alloying is the main mechanism to increase strength of steel. However, high carbon contents deteriorate many other properties like ductility, toughness and weldability. Mechanical properties have become essential in applications like steel castings for valves, flanges, fittings, and other containing parts, intended primarily for low-temperature service.

Low alloy steel grades could be the right solution. However the problem of improving the impact transition temperature (ITT) should be taken into consideration.

Consequently, efforts were made in the present study to develop low alloy steel grades with high mechanical properties in addition to better toughness behavior at low temperatures.

Three steel alloys were processed with different chemical compositions. The first alloy was matched with ASTM A352 grade LC2. The second one was developed by addition of 1.87% Chromium and 0.536% Molybdenum to the melt to meet the composition of ASTM A352 grade LC2-1. 0.06% Niobium was added to the rest of the last portion of the melt for grain refining process in order to create the last alloy.

Hardness as well as tensile and impact testing at different subzero temperatures have been carried out to characterize the mechanical behavior of different alloys. Microstructure investigations for different alloy conditions were also carried out. Furthermore, SEM and fractographic studies have been used to confirm what have been obtained by mechanical testing.

As cast microstructure of alloy 2 was heterogeneous containing ferrite matrix with included martensite aggregates. Austenitizing at 900 °C followed by oil quenching and later by 590 °C tempering results in homogeneous-tempered martensite creation. Down to -73 °C, the impact transition temperature (ITT) was not detected.

Molybdenum and Chromium alloying creates a very fine martensitic structure in the modified alloy LC2-1.

Unsuitable quenching-tempering of alloy LC2-1 accelerates the ductile- brittle transition temperature (ITT) to -30 °C.

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CHAPTER 1

INTRODUCTION AND AIM OF THE WORK

Chapter 1

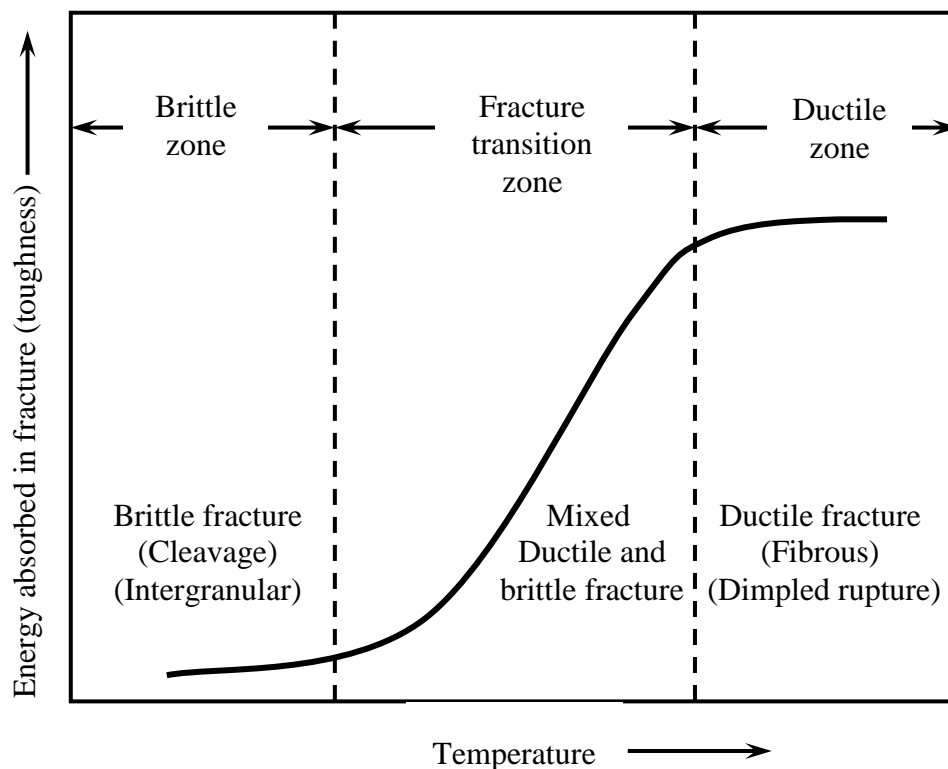
Introduction

1.1 Introduction

Steel is the most important commercial alloy. It is the most effective alloy for our industrial applications. A wide variety of steels are in common use today. Of course, "steel" is not a single alloy, but instead is a bewildering array of compositions whose common component is iron. The microstructure of steel is the key to its behavior. The crystal structure, grain size, carbon content and arrangement of the microconstituents (bcc ferrite, bct martensite, fcc austenite, orthorhombic cementite, etc.) determine steel properties. The present study deals with cast carbon low alloy steel. Alloy steels contain alloying elements other than carbon and iron. The alloying elements mainly make it easier to obtain the phase transformations necessary for successful heat treatment. A few alloying elements are added for solid-solution strengthening, and a couple of these alloying elements are added for control of undesirable and unavoidable impurities. Alloy steels can be classified into low alloy steels and high alloy steels. Low alloy steels contain alloying elements less than 10% although high alloy steels contain more than 10% of the alloying elements.

Critical structural components must be fabricated from steels that exhibit adequate low-temperature fracture toughness because of the serious consequences of failure due to brittle fracture.

Low alloy steel is used for steel castings which operate at low temperature applications. It is known that the ambient temperature has a great effect on the mechanical behavior of steel. Generally, steels behave brittle as they are subjected to low temperature as shown from [figure 1.1](#).



[Figure 1.1](#) Effect of temperature on toughness

It is also clear that steel changes from ductile phase to brittle phase through fracture transition zone.

Consequently steel must be designed to overcome or to delay the ductile to brittle transition temperature to withstand high toughness to resist the impact load at subzero temperatures. The impact transition temperature for all alloys created to manufacturing gas pipe fitting must be shifted toward the subzero degrees. The transition temperature can be shifted to the subzero degrees by two techniques. The first one could be implemented by adding alloying elements such as Nickel and Niobium etc. where Nickel increase toughness and shifts to sub-zero transition temperature. Niobium operates as a grain refiner to the low alloy steel. Grain refinement is considered as the most effective tool to fulfill the previous requirements (high strength combined with excellent toughness). The most effective means for grain refinement at reasonable costs is achieved by microalloying processing. Heat treatment like quenching and tempering is a second technique which affects on the transition temperature. Heat treatment to low alloy steel increases toughness at low temperature.

1.2 Aim of the work

- The aim of this investigation was to develop cast carbon low alloy steel grades suitable for low temperature applications by micro alloy technology.
- The developed grades are subjected to quenching and tempering heat treatment to enhance the mechanical properties.

CHAPTER 2

LITERATURE SURVEY

Chapter 2

Literature Survey

2.1. Low alloy steels

2.1.1. Definition

Low-alloy steels contain, in addition to carbon, alloying elements up to a total alloy content of 8%. The maximum amount of each alloying element in low alloy cast steels must not exceed the values indicated at table 2.1 [1]:

Table 2.1 Amounts of alloying elements considered for low-alloy cast steel

Element	Manganese	Silicon	Nickel	Copper	Chromium	Molybdenum	Vanadium	Tungsten
Amount, %	1.00	0.80	0.50	0.50	0.25	0.10	0.05	0.05

Steel that contains little amounts of intentionally added materials (less than 10% alloy), which change the property of the metal is called low alloy steel [2].

For many low-alloy steels, the primary function of the alloying elements like manganese, molybdenum, chromium, and nickel is to increase the hardenability in order to optimize mechanical properties and toughness after heat treatment.

Carbon content is usually below 0.25 percent and often below 0.15 percent. Typical alloys include nickel, chromium, molybdenum, manganese, and silicon, which are added to increase low-temperature notch toughness.

2.1.2. Advantages and disadvantages of low alloy steel

Low alloy steels have the following advantages [2].

1. Greater hardenability.
2. Less distortion and cracking during quenching.
3. Greater stress relief at given hardness.
4. Less grain growth.
5. Higher elastic ratio and endurance strength.
6. Greater high temperature strength.
7. Better machinability at high hardness.
8. Greater ductility at high strength.

However it contains some disadvantages as illustrated below [2].

1. High cost due to alloying elements.
2. Special handling.
3. Tendency toward austenite retention.
4. Temper brittleness in certain grades.

2.1.3. Classification of low alloy steels

Low-alloy steels can be classified according to either chemical composition or Heat treatment [3].

- Chemical composition
 1. Nickel steels.
 2. Nickel-chromium steels.
 3. Molybdenum steels
 4. Chromium-molybdenum steels
- Heat treatment
 1. Quenched and tempered steels.
 2. Normalized and tempered steels.
 3. Annealed steels.

2.2. Mechanical properties of low alloy steel

Mechanical properties include toughness, tensile strength, and hardness. The most effective mechanical property for steel at low temperature is toughness.

2.2.1. Toughness

Toughness is the ability of materials to absorb energy during the process of plastic deformation and fracture, and is the synthetic display of strength and plasticity [4].

Toughness is an indication of the capacity of steel to absorb energy and is dependent on strength as well as ductility. Notch toughness is an indication of the capacity of steel to absorb energy when a stress concentrator or notch is present [5].

2.2.2. Relation between Steel toughness and low temperature applications.

The ductile-to-brittle transition in steels remains one of the important issues of materials science, although it has been subjected to extensive research. The integrity assessment of key safety components made of steel, such as castings for valves, flanges, fittings, and other pressure-containing parts depends on the material's resistance to brittle fracture [6].

Low-alloy steels are key materials used for nuclear reactor facilities such as pressure vessels, compressors, and steam generators. The most critical properties required for these low-alloy steels are sufficient strength to withstand the inner pressure and a high fracture toughness that can ensure safety against momentary impact due to unexpected accidents [7].

Steels used to transport crude oil or natural gas over a long distance under a high pressure essentially require high strength and toughness, and thus there have been many studies dedicated to these purposes [8].

Steels with excellent low temperature toughness help natural resources (natural gases) transported at low temperatures. Since fracture toughness tends to decrease as strengths increase, structural integrity at low temperatures should be seriously considered in order to develop new high-strength, high-toughness steels [8].

It was found that the excellent low-temperature toughness is useful in the manufacture of low-temperature pressure vessels [9].

It has been well known that among the factors affecting material fracture characteristics, temperature and strain rate are two very important external ones. Most brittle fracture accidents with low stress occur in steel structures due to low temperature and dynamic loading conditions. The mechanism of plastic deformation and fracture of materials may change at different temperatures and strain rates [10].

In low alloy steels, a unique characteristic is found during impact testing over a temperature range of approximately 120 to -130 °C. This characteristic is a ductile-to-brittle transition in toughness. At the higher end of the temperature range, the fracture behavior is ductile with an accompanying large degree of plastic deformation. The ductile mode of fracture is most commonly associated with microvoid coalescence. At the lower end of the range the fracture is brittle, and the mode of fracture is cleavage with little or no plastic deformation.

Figure 2.1 represents a Charpy curve showing a typical ductile-to-brittle transition in steels. The plot shows absorbed energy versus test temperature. The stable region at the high temperatures is called the upper shelf, and the stable region at the lower temperatures is called the lower shelf. The region between the upper and lower shelves that displays a mixture of ductile and cleavage fracture is called the transition region [12].

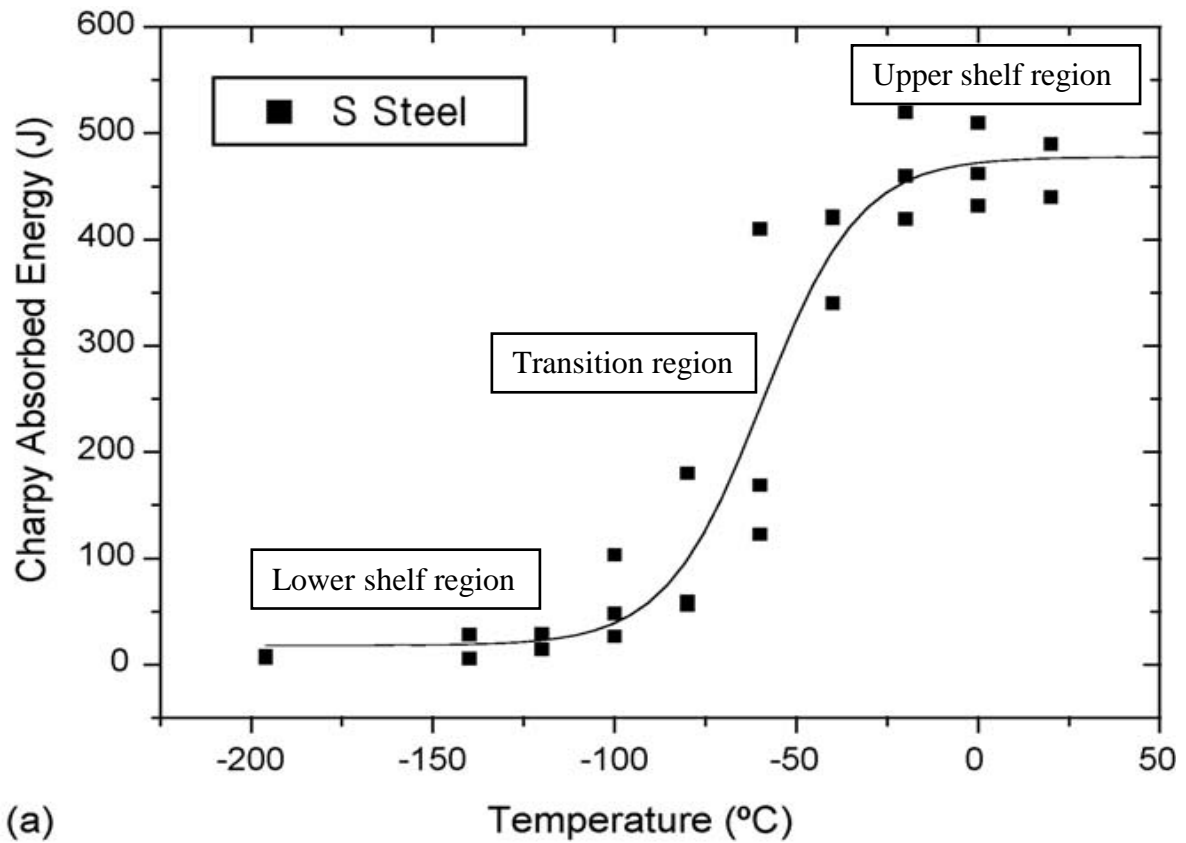
When the ambient temperature drops, the toughness of materials also decrease and it becomes very low at a certain low temperature. This is called cold brittleness, and the temperature at which the material turns from a tough state to a brittle state is called the ductile–brittle transition temperature [4].

The influence of temperature on impact toughness and fracture behavior of alloy steel (AISI Classification 8320) is presented and discussed. Impact toughness decreased with a decrease in test temperature as illustrated in figure 2.2. [13]

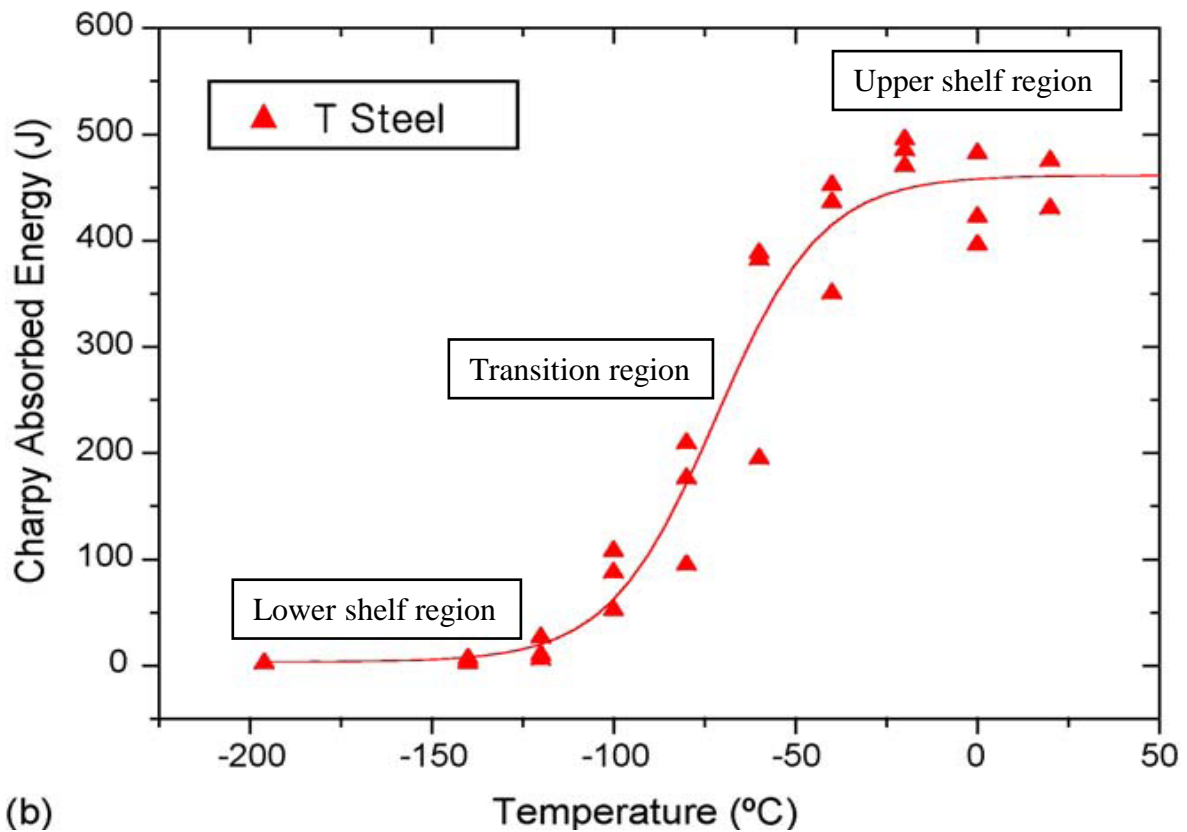
Composition of the 8320 steel chosen for this experimental study is provided in table 2.2.

Table 2.2 Composition of 8320 steel [13].

Element	C	Mn	Si	Cr	Ni	Mo
Weight %	0.20	1.25	0.25	0.60	0.30	0.18



(a)



(b)

Figure 2.1 Variation of Charpy impact energy of the (a) Steel rolled in the single phase region and (b) Steel rolled in the two phase region in the temperature range from -196°C to room temperature. [9]

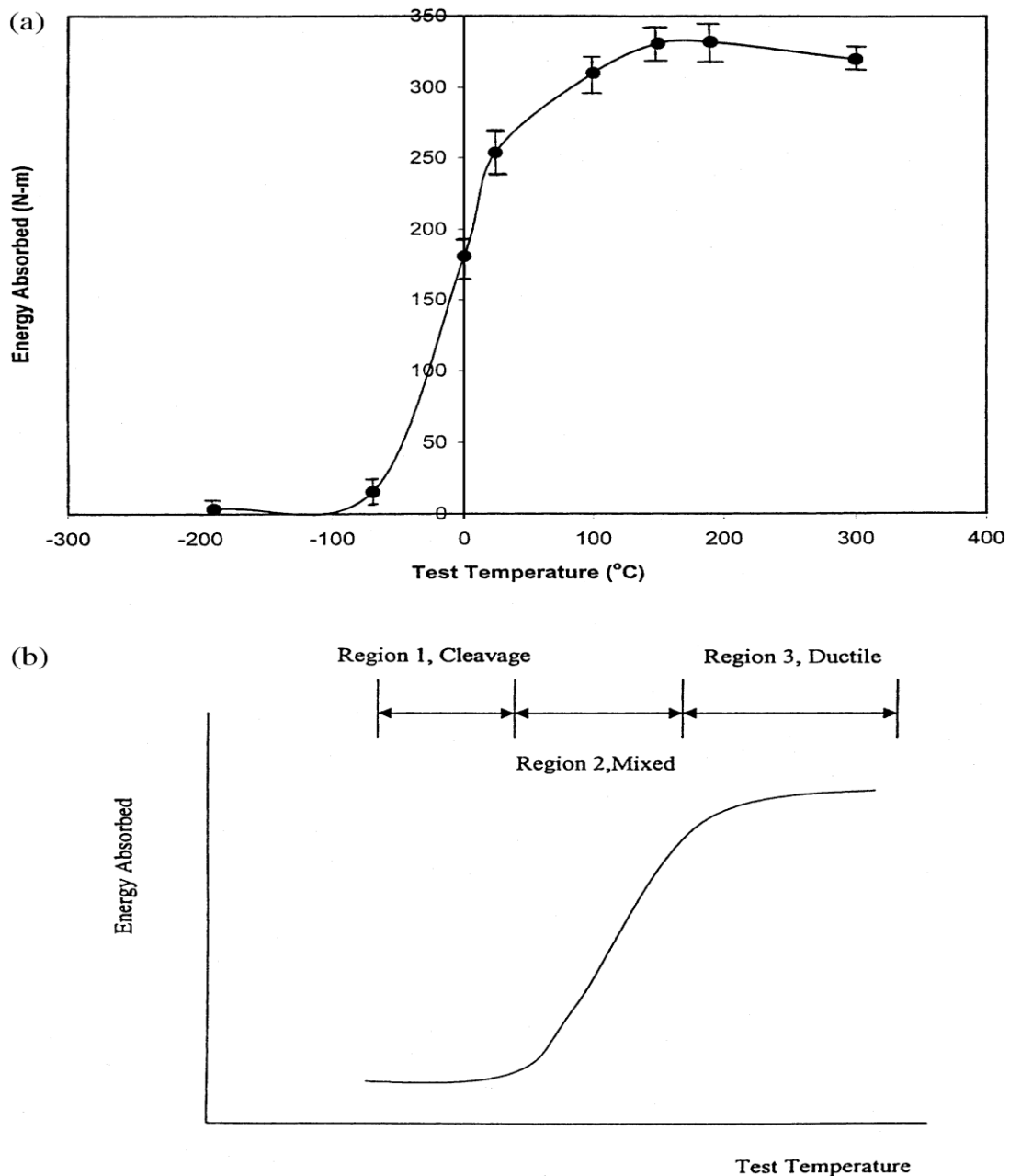


Figure 2.2 (a) Variation of energy absorbed (Nm) as a function of test temperature.
 (b) The three distinct regions of a Charpy Impact test curve [13].

Results of the impact test are as shown in **Figure 2.2**. As expected, the energy absorbed to failure decreased with a decrease in test temperature. A variation of energy absorbed (Nm) follows the characteristic ‘S’ shape curve **Figure 2.2**. The ‘S’ curve is composed of essentially three regions. Region 1 is referred to as the lower shelf. The total energy absorbed to fracture in the lower shelf regime is relatively small, with limited crack propagation and failure predominantly by cleavage. Region 2 is characterized by a rapid increase in the total energy absorbed to fracture with an increase in test temperature. Such behavior is ascribed to a combination of: (a) an increase in the size of the plastic zone ahead of the propagating cracks; and (b) ductile tearing at the crack front prior to onset of instability. Region 3 is referred to as the ‘upper shelf’, with failure resulting from fracture by ductile tearing. As a result, the energy absorbed in the region of upper shelf can be quite large. The difference between Region 2 and Region 3 is the amount of tearing associated with ductile failure [13].

2.2.3. Factors affecting toughness.

Fracture toughness and overall fracture resistance of a high strength low alloy steel is governed by the mutually competitive yet interactive influences of [13]:

- (a) Alloy composition.
- (b) Processing history and development of intrinsic microstructural features;
- (c) Temperature of operation;
- (d) Loading-rate; and
- (e) Potential constraints at the crack (flaw) tip.

2.2.4. Effect of chemical composition on toughness.

Alloying elements can affect the constitution, characteristics, and behavior of alloy steels in many ways. Some of the major effects of alloying elements are, strengthening of ferrite, formation of special carbides and compounds, shifting of critical temperature and compositions, and lowering of critical cooling rate [14].

The composition of steel, as well as its microstructure and processing history, significantly affect both the ductile-to-brittle transition temperature range and the energy absorbed during fracture at any particular temperature. The effect of various alloying elements in addition with microstructural and processing variables are intimately interrelated; in practice, it is difficult to change one variable without affecting another [15-16]. Each individual alloying element contributes to toughness to varying degrees [11].

2.2.4.1. Effect of carbon

Increase of carbon content increases transition temperature and decreases upper-shelf fractural energy primarily as a result of increased strength and hardness. These effects, measured by Charpy V-notch impact testes, are shown in figure 2.3. Consequently, for maximum toughness, the carbon content should be kept as low as possible, consistent with strength requirements. Low-carbon steels tend to have very steep transition curves [11].

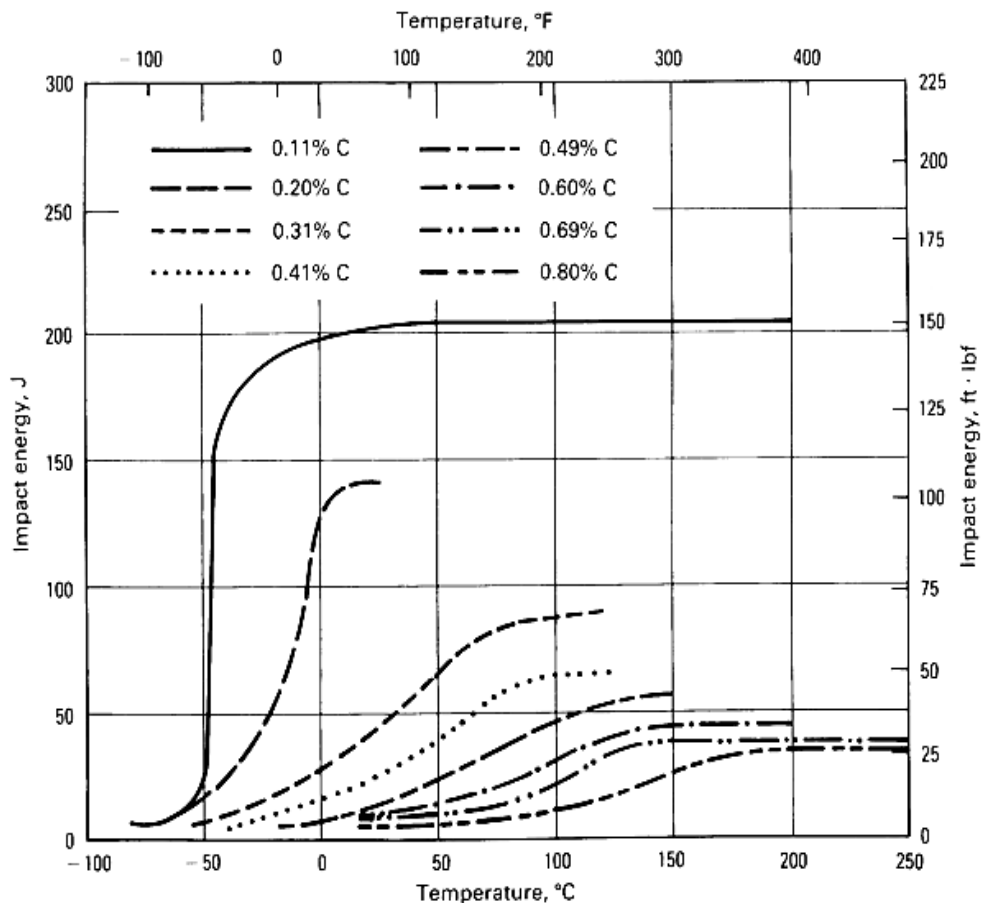


Figure 2.3 Effect of carbon percent on toughness [17]

2.2.4.2. Effect of Manganese

Manganese has a variety of effects on transition temperature. In low-carbon steels, it can substantially reduce the transition temperature, as shown in the figure 2.4 (a). In higher carbon steels, manganese may be less beneficial. As illustrated in figure 2.4 (b), increasing the manganese content of a normalized medium-carbon steel lowered the impact transition temperature, probably because the additional manganese reduce the pearlite interlamellar spacing (the spacing between the alternating plates of ferrite and cementite in pearlite). In hardened and tempered steel, manganese can have the opposite effect. Manganese can make the steel susceptible to temper embrittlement, and it may cause the formation of less tough upper bainite (rather than fine pearlite) during normalizing [11].

Manganese helps in the formation of Manganese carbides, which contributes to enhancing matrix strength [13].

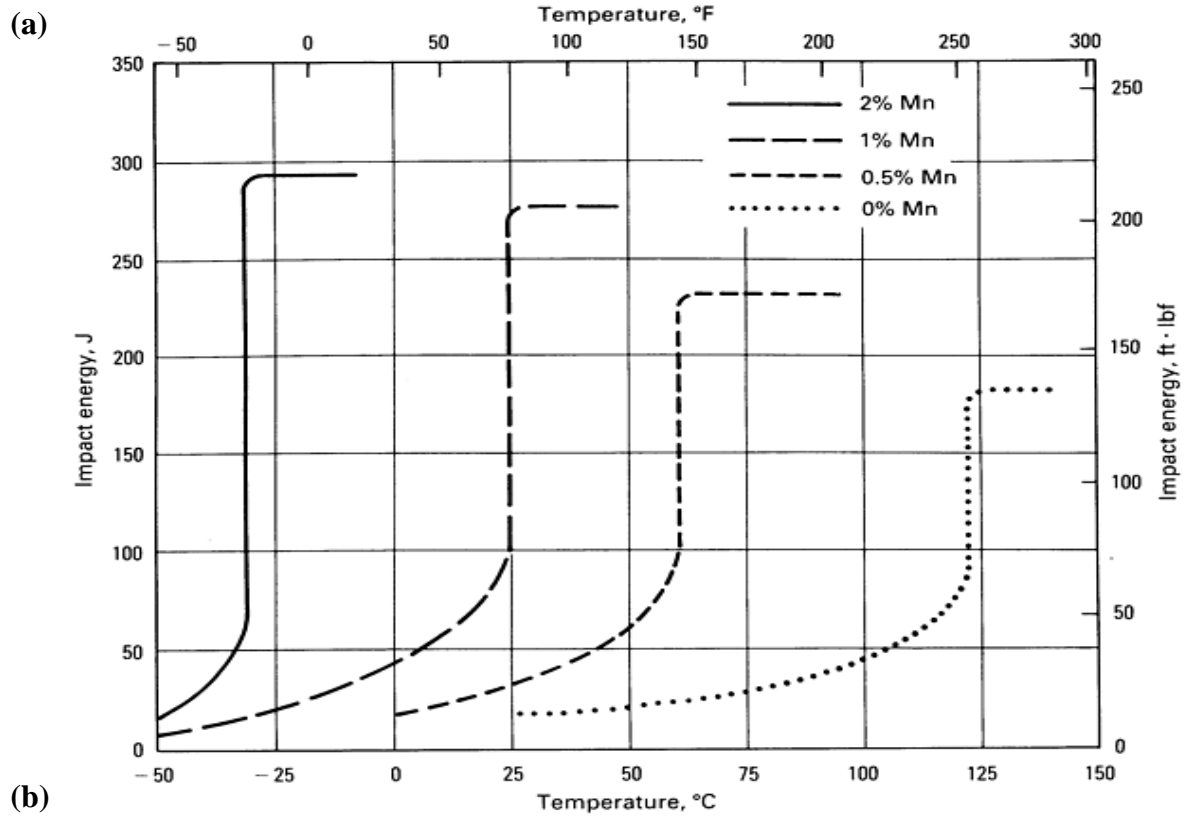


Figure 2.4 Effect of Manganese on Toughness (a) At 0.05% C [18] (b) At 0.30% C [19]

2.2.4.3. Interactive effect of Carbon and Manganese

The increasing of Mn/C ratio appreciably decreases the transition temperature.

Figure 2.5 shows the effect of Mn/c ratio for various carbon contents.

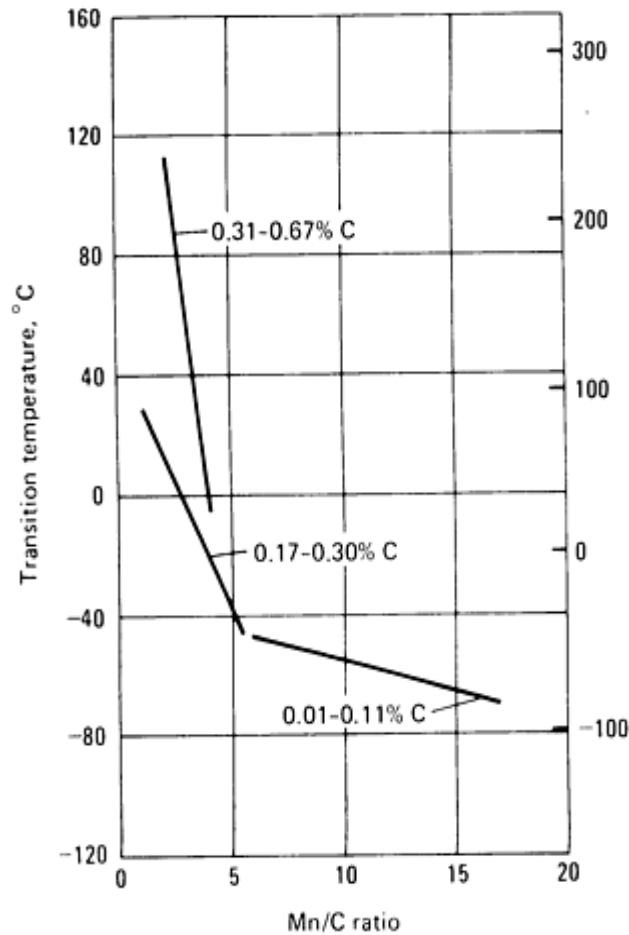


Figure 2.5 Interactive effects of Carbon and Manganese [19]

2.2.4.4. Effect of Nickel

Nickel, when used as an alloying element in constructional steels, is a ferrite strengthener. Because nickel does not form any carbide compounds in steel, it remains in solution in the ferrite, thus strengthening and toughening the ferrite phase. Nickel steels are easily heat treated because nickel lowers the critical cooling rate. In combination with chromium, nickel produces alloy steels with greater hardenability, higher impact strength, and greater fatigue resistance than can be achieved in carbon steels [20].

Nickel, like manganese, is useful for improving the notch toughness of steel at low temperatures. Nickel is less effective in improving the toughness of medium-carbon steels than low-carbon steel. The high nickel content reduce upper-shelf fracture energy- but to a level that is steel quite acceptable for most applications. The effect of varying nickel content on the notch toughness of steels is shown in Figure 2.6 [11].

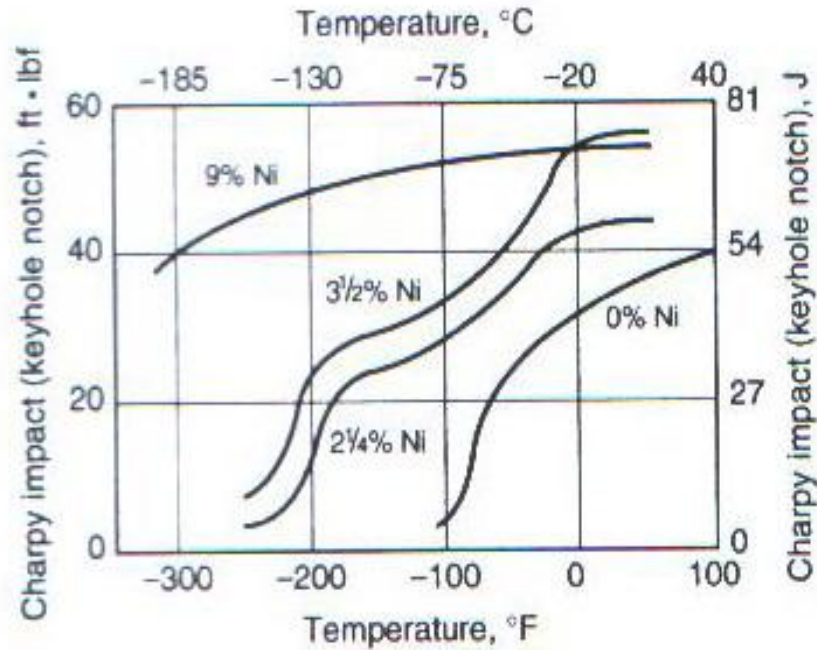


Figure 2.6 Effects of Nickel percent on Toughness [21]

2.2.4.5 Effect Chromium

Chromium raises the transition temperature slightly. Chromium is usually added to increase hardenability. The increase in hardenability is often sufficient to develop a martensitic microstructure, which provides high upper-shelf energy [11].

Chromium helps in the formation of carbides, which contributes to enhancing matrix strength [13].

2.2.4.6. Effect of Molybdenum

Molybdenum in the typical quantities in low alloy steels (up to about 0.40%) raises the 50% FATT. Molybdenum is frequently used to increase hardenability, and it influences notch toughness primarily through its effect on microstructure. About 0.5 to 1.0 % Mo can be added to alloy steels to reduce their susceptibility to temper embrittlement, but it is effective only for relatively short heating times at embrittling temperatures. Molybdenum appears to delay rather than eliminate temper embrittlement, because steels containing small amounts of this element have become embrittled upon prolonged exposure within the embrittling temperature range [11].

Molybdenum helps in the formation of carbides, which contributes to enhancing matrix strength. Molybdenum assists in refining the grain size and thereby contributing to an improvement in toughness [13].

2.2.4.7. Effect of Copper

Copper in steels appears to be moderately beneficial to low-temperature notch toughness. However, copper promotes precipitation hardening in steel and, as a result, may adversely affect notch toughness, particularly if the tempering temperature is between 400 and 565 °C [11].

2.2.4.8. Effect of Phosphorus

Phosphorus has strongly deleterious effect on the notch toughness of steel. It raises the 50% FATT about 7 °C for each 0.01%P and reduces upper-shelf energy. In addition, phosphorus increases the susceptibility of some steels to temper embrittlement [11].

2.2.4.9. Effect of Sulfur

The effect of sulfur on the notch toughness of steel is directly related to deoxidation practice. For rimmed, semikilled, and silicon killed steels, sulfur in amounts up to about 0.04% has negligible effect on notch toughness, sulfur has strong directional effect on harpy results depending on the inclusion types percent (for example, sulfides, oxides, and complex nonmetallics) [11].

2.2.5. Strength and ductility.

Ductility is inversely proportional to the strength, or hardness, of the cast steel. Actual ductility requirements vary with the strength level and the specification to which steel is ordered. Yield strength is a primary design criterion for structural applications. Therefore, figure 2.7 plots tensile strength, ductility (as measured by elongation), and toughness (based on Charpy V-notch impact energy) in terms of yield strength. Quenched-and-tempered steels exhibit higher ductility values for a given yield strength level than normalized-and-tempered steels [12].

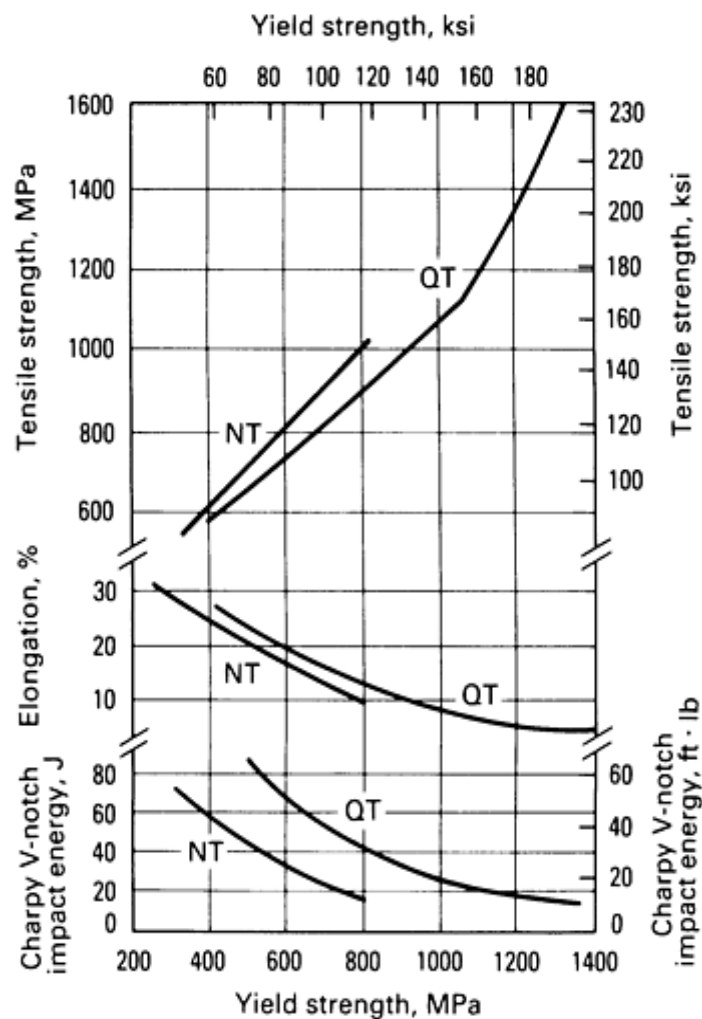
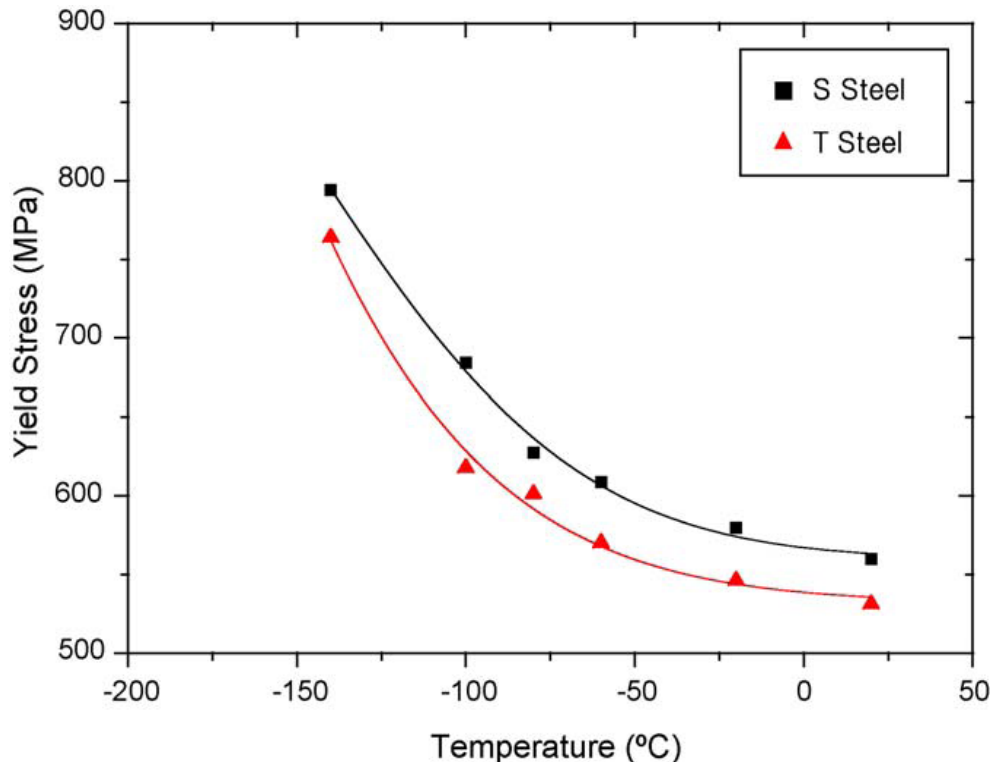


Figure 2.7 Room-temperature properties of cast low-alloy steels. QT, quenched and tempered; NT, normalized and tempered [12]

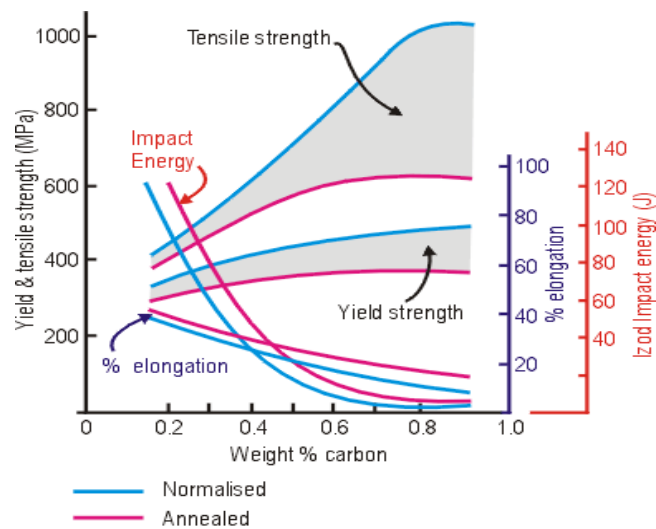
The tensile strength increases slightly with decreasing experiment temperature as shown in [figure 2.8](#); the elongation and reduction of area remain almost unchanged with the experimental temperature [\[9\]](#).



[Figure 2.8](#) Variation of yield stress of the S and T steels in the temperature range from $-140\text{ }^{\circ}\text{C}$ to room temperature [\[8\]](#).

2.3. Strengthening mechanisms of low alloy steels.

Carbon is one of the most important alloying elements which can change the flow behavior as well as the microstructure and kinetics of metallurgical transformation of steel. Increasing carbon content increases strength significantly. However, it deteriorates ductility, toughness and weldability ([Figure 2.9](#)) [\[22\]](#).



[Figure 2.9](#) Effect of carbon content on steel properties [\[22\]](#)

This is why low carbon steels are highly demanded for most modern applications. The problem of low strength is solved by using other strengthening methods. By substituting carbon by other strengthening mechanism, shown in **Figure 2.10**, a further increase in toughness, formability and weldability is obtained [22].

Figure 2.11 shows the effect of alternative strengthening mechanisms on toughness.

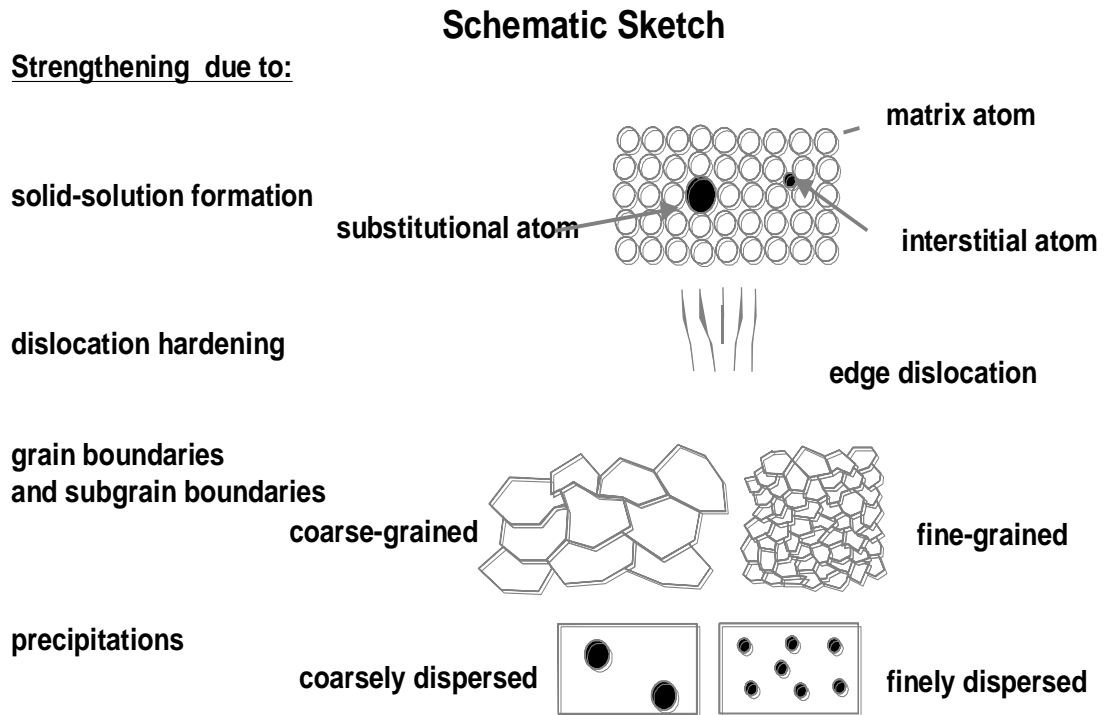


Figure 2.10 Schematic sketches of different strengthening mechanisms of low carbon steel [22]

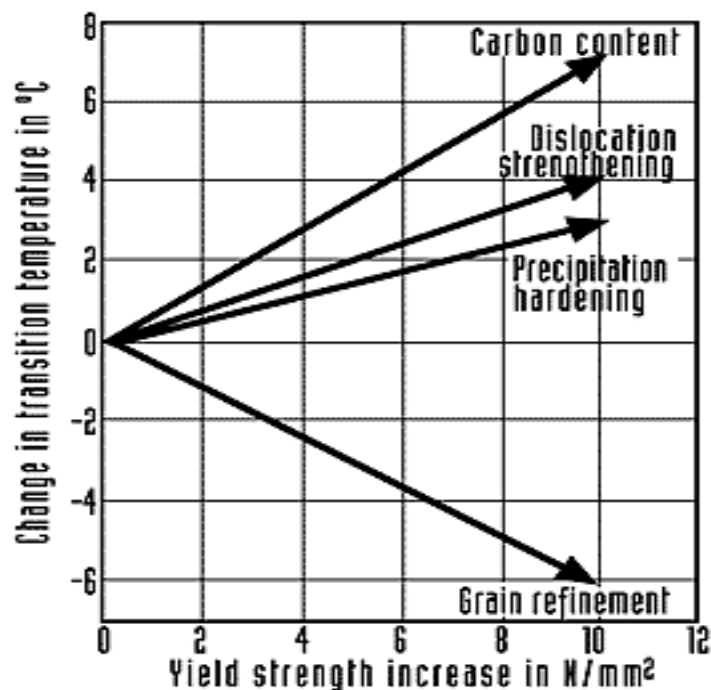


Figure 2.11 Effect of different strengthening mechanisms on impact toughness of steel [22]

From crystal defect theory, the metal yield strength is proportional with square root of the dislocation density. So, the strength increases with increasing of the dislocation density. Because of existing of the fine crystal grain, there is more grain boundary, where the movement of the dislocation can be hindered and piled up. Hence, higher stress is necessary to start the movement of the dislocation. So, the strength is improved. Therefore, increasing the grain boundary by reducing the grain size can improve the yield strength significantly. This is the main mechanism of the fine-crystal strengthening of the materials. The main parameters that determine the final ferrite grain size are: the chemical composition, the austenite grain size, the cooling rate [22].

2.4. Effect of grain size on the mechanical properties of low alloy steel.

The grain size is yet another factor which plays a significant role in controlling the fracture toughness of alloys [23].

A decrease in grain size reduces the transition temperature of steel as indicated in figure 2.12; therefore, hot deformation practices and secondary heat treatment are usually designed to produce fine grains. In addition to improve notch toughness, a fine grain size increases the strength of steel. Thus, refinement of grain size is the most important and most effective way to increase both strength and toughness. When steel is heated, small austenite grains form at temperature above the temperature at which austenite begins to form upon heating, A_{c1} . Grain size continually increases with time at temperature, and higher temperature result in faster grain growth. The strength, ductility, and impact toughness of coarse-grain metals are impaired not only by the large grain size but also by the grain-boundary precipitation. Generally, when a metal has been overheated and incipient melting has not occurred, reheat treating at proper time and temperature will restore a desirable small grain structure and satisfactory properties.

Qualitatively, the embrittling effect of large grains in ferritic steel can be explained by stress concentration at the ends of slip bands and at grain boundaries. The larger the grains, the longer slip bands and the greater the stress concentration. Severe stress concentration will induce nucleation of microcracks, which in turn may cause early and catastrophic fracture [11].

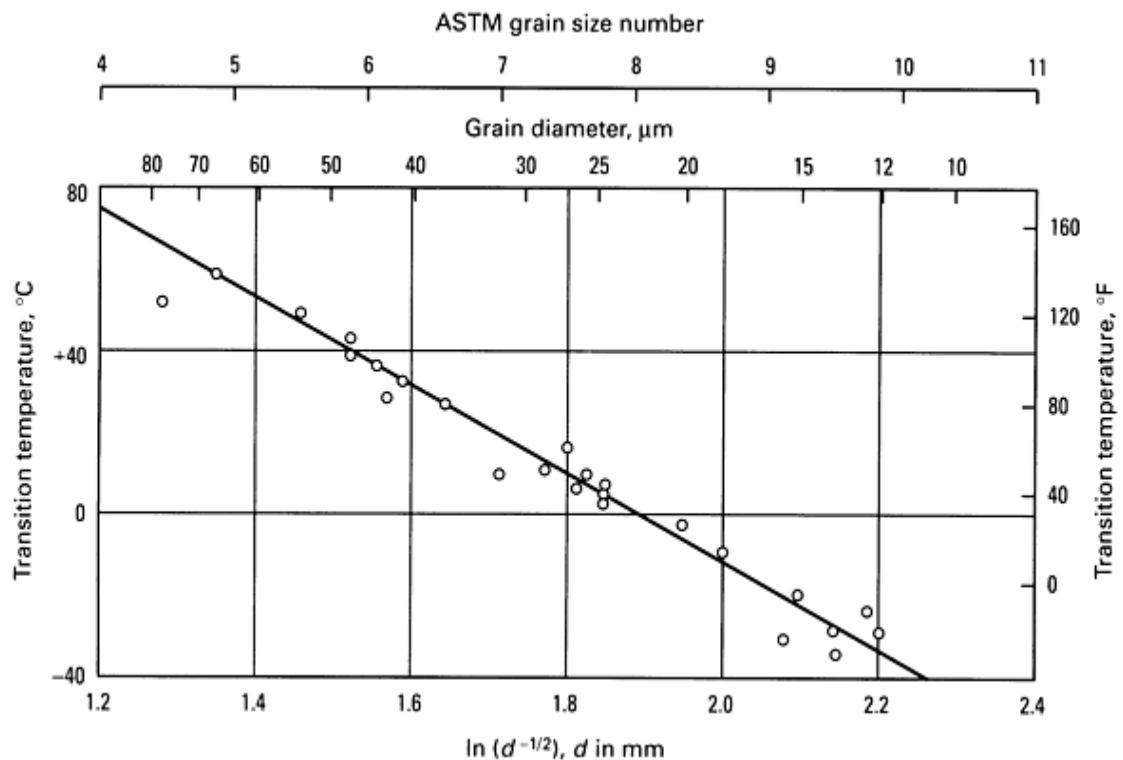


Figure 2.12 Effect of Grain Size on Notch Toughness [24]

2.5. Grain refinement in low alloy steel

Steel is still one of the traditional engineering materials widely used in industry. The high strength and high toughness steel is the most desirable product. However, in fact, strength and toughness are normally contrary. If the strength of steel increases, its toughness will normally decrease and vice versa. The composition and microstructure of the steel are primary factors controlling the strength and the toughness. Thus the grain refinement is a highly effective method to improve both the strength and the toughness [25].

The role of microalloying is to improve both the strength and toughness of steels by grain refinement. Grain refinement results from the inhibition of austenite grain growth during reheating and retardation of recrystallization by the fine carbide and nitride precipitates [26].

Achievement of a fine grain size generally leads to improved mechanical properties and structural uniformity of most metals and alloys. Thus, a fine grain size in castings is important for the service performance of cast products and is also important for the final properties of semifabricated items. Grain refinement is a traditional instrument for increasing the strength of materials.

Grain refinement of low alloy steel can be made by two different methods.

- With additions of grain refining elements such as aluminum, niobium, vanadium and titanium, all of which produce small sparingly soluble precipitates [26].
- By using heat treatment such as quenching and tempering.
- Rate of cooling due to the type of the moulding sand.

2.6. Effect of Niobium on the mechanical properties of low alloy steel.

Microalloyed steels have received considerable interest and have been used widely in industrial applications over many years. Nb is one of the most frequently added microalloying elements because of its strong effect on microstructures and its mechanical properties. The element Nb remains in solution at high temperatures and upon cooling it combines with C and N to form carbonitride precipitation [27].

The main goal during processing of low alloy steels is to obtain a fine microstructure in order to improve the mechanical properties of the steel. For this reason, Nb is one of the most frequently added microalloying elements because of its significant effect on austenite recrystallization. Niobium belongs to the family of metallic elements known as transition metals. Niobium is a ferrite stabilizer. However, additions of up to 0.10 to 0.20 percent lower the phase transformation temperature. Thus, in small quantities niobium acts as a γ stabilizer.

Niobium has a marked effect on reduction of the solubility of carbon in austenite and ferrite as a result of the ready formation of niobium carbide. Niobium shows a strong tendency to form carbonitrides, but relatively little tendency to form oxides, sulfides or solid solutions of these compounds. Microalloyed steels contain both carbon and nitrogen and when niobium precipitates it does so as niobium carbonitride. The crystallography of “NbC” is very similar to “NbN”. Hence, it is quite reasonable to expect the two to have complete solid solubility, i.e. forming a carbonitride [22].

Other studies of the composition of the carbonitride which forms in Nb-bearing microalloyed steels have shown a direct relationship between the composition of the carbonitride and the composition of the steel. The carbonitride becomes more nitrogen-rich with increasing the N/C ratio in the steel. The composition of the carbonitrides in any given steel can depend upon the

thermal conditions under which they form. The data indicate that the precipitates contain more nitrogen when formed at higher temperatures. Ouchi, et al. observed that the presence of other elements such as titanium and aluminum, that have strong nitride-forming tendencies, will affect the amount of nitrogen in NbC_xN_y. The solubility of Nb in steel depends on carbon content and temperature. The amount of Nb in solution at any temperature can be calculated from the following equation [22]:

$$\log[\text{Nb}] \cdot [\text{C}] = 3.36 - \frac{7167}{T}$$

Niobium in solid solution is available for the formation of niobium carbide precipitates in ferrite, which have the appropriate size for additional strength increase via precipitation hardening. This strength increase amounts to about 100 MPa for 0.03 % niobium in solid solution, when the particle size of the ferrite precipitates is 1.5 to 2 nm. These small particles are difficult to detect and just particles with a size of 4 nm and more can be found by transmission electron microscopy. It has been confirmed, that these particles are cubic NbC not containing any other element than niobium and carbon having a lattice parameter of 0.446 nm.

How the solute Nb is responsible for the improvement in FATT. Is it the grain refinement of 20% of the structure that is polygonal ferrite? Or, is it the presence of low carbon bainite. In simple terms, this effect on toughness is likely due to the Nb acting as both a hardenability agent and as a grain refiner. There is no doubt that the addition of Nb to most low alloy steels results in higher yield strengths [22].

Niobium is a very important alloying element because it can not only restrain the growth of austenite grain, but also inhibit austenite recrystallization, so controlled heating and controlled cooling technology is very effective to increase the strength and toughness of the steels containing niobium. Nb can act as either a solute or precipitate in austenite, each with a different effect. For precipitation to occur in austenite there must be existed adequate levels of both supersaturation and interpass time. Hence, slow processing in austenite [22].

The suppression of grain boundary migration due to microalloying is caused by (1) the solute dragging effect caused by segregation of alloying elements to the boundaries, or (2) the pinning effect caused by carbonitride precipitates of the alloying elements in the suppression of grain boundary migration.

The radius of Fe atom is 1.26Å and electronegativity is 1.8, while the radius of Nb atom is 1.47Å and electronegativity is 1.8. The radius and electronegativity between Fe and Nb atoms differ bigger, so Nb atoms are easier to segregate under dislocation line as illustrated in figure 2.13. Therefore, the climb velocity of dislocation obviously decreases due to segregation of Nb atoms, which would inhibit austenite static and dynamic recrystallization [22].

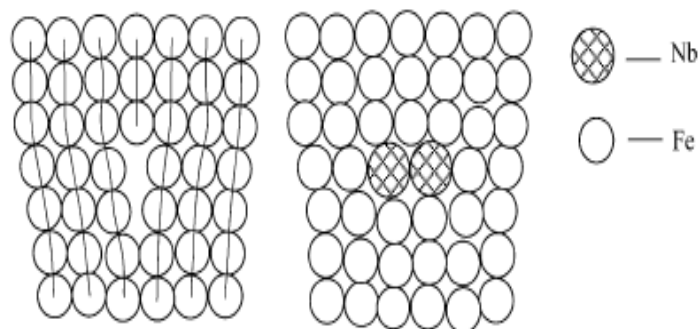


Figure 2.13 Sketch map of dislocation climbing being inhibited by atoms segregating at dislocations [22]

It can be seen that the solute atoms whose radius and electronegativity are similar to Fe atom, such as Ni, Cr, and Mn etc., which have very weak hindrance to austenite recrystallization are suitable to form substitutional solid solutions strengthening mechanism. Yet Nb atom is the strongest in inhibiting austenite recrystallization. Therefore, drag mechanism of solute plays important role in inhibiting recovery and recrystallization under the circumstance that Nb(C,N) particles do not precipitate. microcontent solution Nb can effectively inhibit austenite recrystallization [22].

2.7. Effect of microstructure on low alloy steel properties.

Like most mechanical properties, the notch toughness of steel can usually be traced directly to microstructure. Because the microstructures of steel are readily observed and classified, it is convenient to attribute the various mechanical properties to the microstructure; even through the properties might also be attributed to the composition and manufacturing history of the steel [11].

The performance of steels depends on the properties associated with their microstructures, that is, on the arrangements, volume fractions, sizes, and morphologies of the various phases constituting a macroscopic section of steel with a given composition in a given processed condition. Because all the phases in steels are crystalline, steel microstructures are made up of various crystals, sometimes as many as three or four different types, which are physically blended by solidification, solid-state phase changes, hot deformation, cold deformation, and heat treatment. Each type of microstructure and product is developed to characteristic property ranges by specific processing routes that control and exploit microstructural changes. Thus, processing technologies not only depend on microstructure but are also used to tailor final microstructures [5].

2.8. Non metallic inclusion (NMIs)

One common phenomenon observed by steel manufacturers is the formation of non-metallic inclusions during the production process. Non-metallic inclusions (NMIs) in steel are chemical compounds of metal with nonmetal which are present in the form of separated particles. Non-metallic inclusions arise because of many mechanical and physicochemical effects which proceed during melting and consolidation of steel.

Although the above mentioned contaminations, in most cases, have negative effect on the properties of final steel product, NMIs can be considered the most important one. Usually clean steel is related in most cases to its content of NMIs.

The amount, distribution, size and chemical composition of non-metallic inclusions have a direct influence on steel properties [28].

NMIs can be classified according to their size, source, chemical composition and morphology

a-NMIs classification according to their size

In general, inclusions are subdivided into macro- ($>20\ \mu\text{m}$), micro- ($1\text{-}20\ \mu\text{m}$), and sub micro-inclusions ($<1\ \mu\text{m}$). As a result, multiple examination methods would be conducted to examine the different inclusion size ranges.

b- NMIs classification according to their source

. They can be divided according to their source to exogenic and endogenic inclusions

Exogenic inclusions introduce to steel melt from outside source as a result of mechanical and chemical erosion of refractory and slag that comes in contact with molten steel. As these

inclusions, usually, of big particle size they can quickly float to molten metal surface and the remaining amount constitutes very small ratio of inclusions that is usually present in steel (< 10%). **Figure 2.14** shows different types and shapes of exogenous inclusions [29-30].

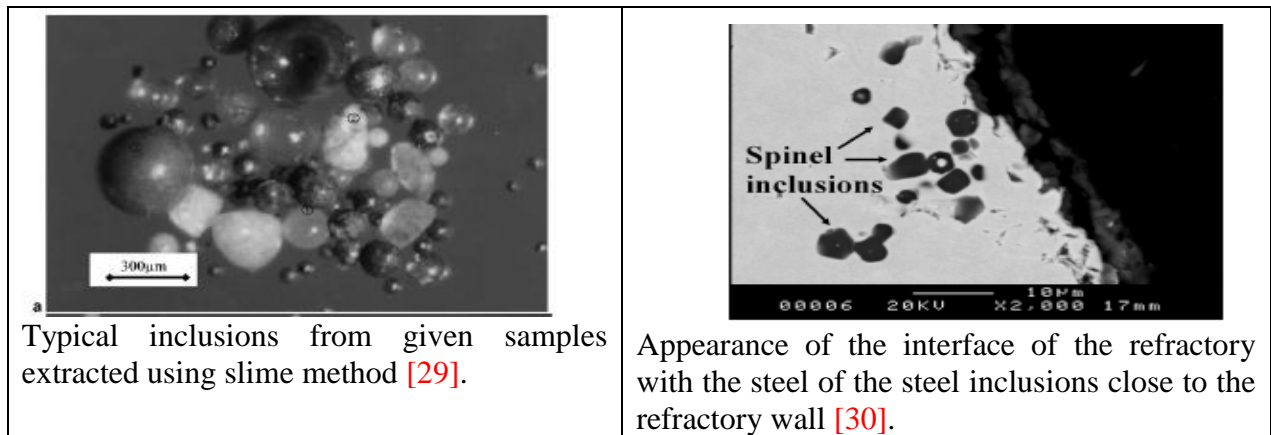


Figure 2.14 different types and shapes of exogenous inclusions.

Endogenic non-metallic inclusions, sometimes called natural, arise because of different reactions during steel production and they include mainly oxides, nitride and sulfides.

Nowadays level of steel production technology allows the elimination of most exogenous and endogenous inclusions from metal. However its general content in different steels can vary between wide limits and has a big influence on the metal properties. **Figure 2.15** shows different types and shapes of endogenous inclusions [31].

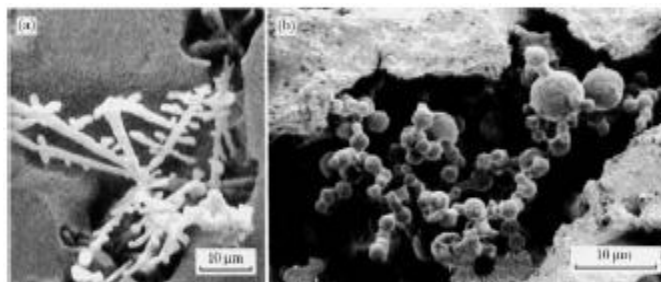


Figure 2.15 alumina dendrite (a) and alumina clusters (b) from deoxidation [31]

c- NMIs classification according to their chemical composition

By chemical composition non-metallic inclusions are divided into the following groups:

1. Oxides (simple- FeO , MnO , Cr_2O_3 , SiO_2 , Al_2O_3 , TiO_2 and others; compound – $\text{FeO.Fe}_2\text{O}_3$, $\text{FeO.Al}_2\text{O}_3$, $\text{Fe.Cr}_2\text{O}_3$, $\text{MgO.Al}_2\text{O}_3$, 2FeO.SiO_2 and others);
2. Sulphides (simple- FeS , MnS , Al_2S_3 , CaS , MgS , Zr_2S_3 and others ; compound – FeS.FeO , MnS.MnO and others);
3. Nitrides (simple – ZrN , TiN , AlN , CeN and others; compound – Nb(C,N) , V(C,N) and others, which can be found in alloyed steel and produced from those elements that has strong nitride generative elements in its content: titanium, aluminium, vanadium, niobium, cerium and others.
4. Phosphides (Fe_3P , Fe_2P and others).

d- NMIs classification according to their morphology

Various inclusion morphologies have been reported in steel: clusters, dendrites, aggregates, small faceted particles, platelets and spherical inclusions, **Figure 2.16**. The different inclusion morphologies have been explained qualitatively. The morphology of the inclusions is controlled by the growth conditions of the inclusions, i.e. the supersaturation degree of the steel with respect to dissolved elements, the holding time, and the liquid flow conditions [32].

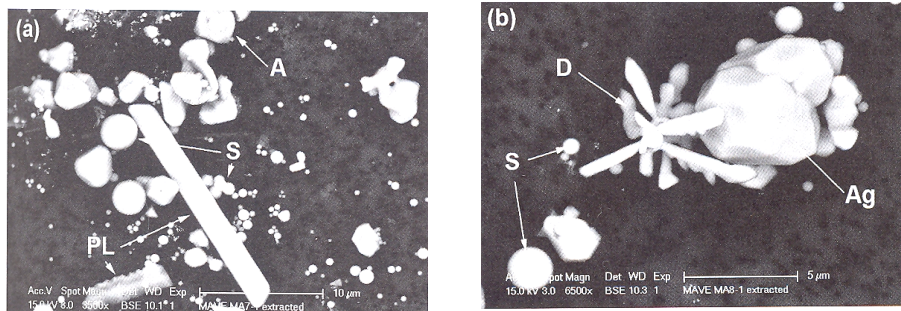


Figure 2.16 Overview of the inclusion morphologies after acid extraction of sample where (S) Spherical particles (A) angular particles (D) Denderitic cluster (PL) plate like.

2.9. Heat Treatment Effect on the Properties of Steel.

Steel is usually defined as an alloy of iron and carbon with the carbon content between a few hundreds of a percent up to about 2 wt%. Other alloying elements can amount in total to about 5 wt% in low-alloy steels and higher in more highly alloyed steels such as tool steels and stainless steels. Steels can exhibit a wide variety of properties depending on composition as well as the phases and microconstituents present, which in turn depend on the heat treatment [33].

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Heat treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics [34].

All casting shall receive a heat treatment proper to their design and chemical composition. It should be recognized that liquid quenching of the ferritic grades is normally required to meet the mechanical properties of heavier sections and will greatly enhance the low temperature properties of thinner sections [35].

Steel castings that have been quenched and tempered have higher notch toughness than similar castings in the as cast, annealed, or normalized condition [10].

2.9.1. Quenching.

Quenching refers to the process of rapidly cooling metal parts from the austenitizing or solution treating temperature, typically from within the range of 815 to 870 °C (1500 to 1600 °F) for steel. Stainless and high-alloy steels may be quenched to minimize the presence of grain boundary carbides or to improve the ferrite distribution but most steels including carbon, low-alloy, and tool

steels, are quenched to produce controlled amounts of martensite in the microstructure. Successful hardening usually means achieving the required microstructure, hardness, strength, or toughness while minimizing residual stress, distortion, and the possibility of cracking [33].

The selection of a quenchant medium depends on the hardenability of the particular alloy, the section thickness and shape involved, and the cooling rates needed to achieve the desired microstructure. The most common quenchant media are either liquids or gases. The liquid quenchant commonly used include:

- Oil that may contain a variety of additives
- Water
- Aqueous polymer solutions
- Water that may contain salt or caustic additives

The most common gaseous quenchant are inert gases including helium, argon, and nitrogen. These quenchant are sometimes used after austenitizing in a vacuum [33].

The ability of a quenchant to harden steel depends on the cooling characteristics of the quenching medium. Quenching effectiveness is dependent on the steel composition, type of quenchant, or the quenchant use conditions. The design of the quenching system and the thoroughness with which the system is maintained also contribute to the success of the process [33].

2.9.1.1. Fundamentals of Quenching and Quenchant evaluation.

Fundamentally, the objective of the quenching process is to cool steel from the austenitizing temperature sufficiently quickly to form the desired microstructural phases, sometimes bainite but more often martensite. The basic quenchant function is to control the rate of heat transfer from the surface of the part being quenched [33].

2.3.1.2. Quenching process.

The rate of heat extraction by a quenching medium and the way it is used substantially affects quenchant performance. Variations in quenching practices have resulted in the assignment of specific names to some quenching techniques [33]:

- Direct quenching
- Time quenching
- Selective quenching
- Spray quenching
- Fog quenching
- Interrupted quenching

Direct quenching refers to quenching directly from the austenitizing temperature and is by far the most widely used practice. The term direct quenching is used to differentiate this type of cycle from more indirect practices which might involve carburizing, slow cooling, reheating, followed by quenching [33].

Time quenching is used when the cooling rate of the part being quenched needs to be abruptly changed during the cooling cycle. The change in cooling rate may consist of either an increase or a decrease in the cooling rate depending on which is needed to attain desired results. The usual practice is to lower the temperature of the part by quenching in a medium with high heat removal characteristics (for example, water) until the part has cooled below the nose of the

time-temperature- transformation (TTT) curve, and then to transfer the part to a second medium (for example, oil), so that it cools more slowly through the martensite formation range. In some applications, the second medium may be air or an inert gas. Time quenching is most often used to minimize distortion, cracking, and dimensional changes [33].

Selective quenching is used when it is desirable for certain areas of a part to be relatively unaffected by the quenching medium. This can be accomplished by insulating an area to be more slowly cooled so the quenchant contacts only those areas of the part that are to be rapidly cooled [33].

Spray quenching involves directing high-pressure streams of quenching liquid onto areas of the workpiece where higher cooling rates are desired. The cooling rate is faster because the quenchant droplets formed by the high-intensity spray impact the part surface and remove heat very effectively. However, low-pressure spraying, in effect a flood-type flow, is preferred with certain polymer quenchants [33].

Fog quenching utilizes a fine fog or mist of liquid droplets in a gas carrier as the cooling agent. Although similar to spray quenching, fog quenching produces lower cooling rates because of the relatively low liquid content of the stream [33].

Interrupted quenching refers to the rapid cooling of the metal from the austenitizing temperature to a point above the M_s Where it is held for a specified period of time, followed by cooling in air. There are three types of interrupted quenching: austempering, marquenching (martempering), and isothermal quenching. The temperature at which the quenching is interrupted, the length of time the steel is held at temperature, and the rate of cooling can vary depending on the type of steel and work piece thickness. Comparisons of direct and interrupted quench cycles are shown in figure 2.17 [33].

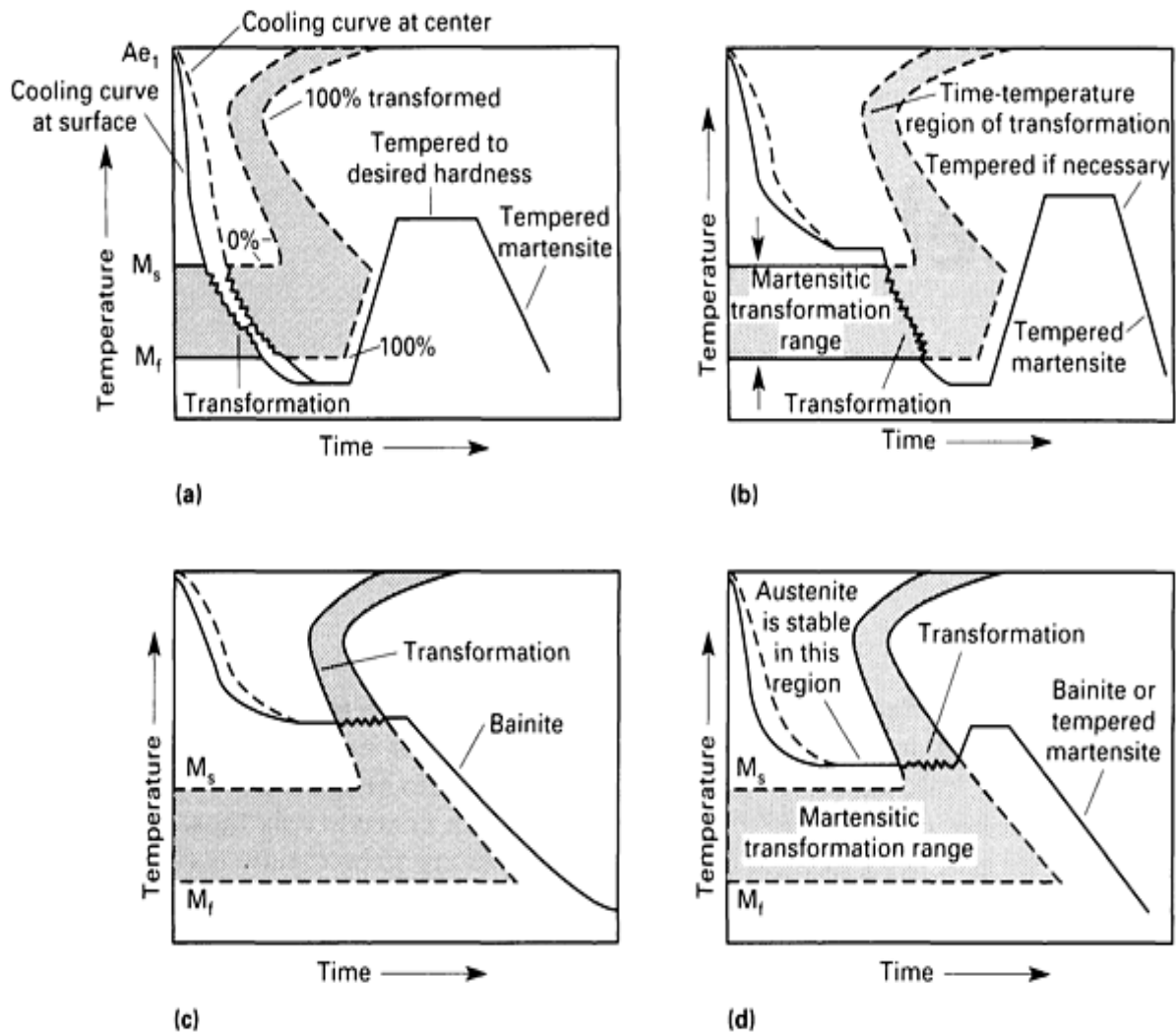


Figure 2.17 Comparison of cooling rates and temperature gradients as workpieces pass into and through martensite transformation range for a conventional quenching and tempering process and for interrupted quenching processes. (a) Conventional quenching and tempering processes that use oil, water, or polymer quenchants. (b) Marquenching, which uses either salt or hot oil as a quenchant. (c) Austempering, which uses a salt as a quenchant. (d) Isothermal quenching, this uses either salt or hot oil as a quenchant [36].

Austempering. Consists of rapidly cooling the metal part from the austenitizing temperature to about 230 to 400 °C (450 to 750 °F) (depending on the transformation characteristics of the particular steel involved), holding at a constant temperature to allow isothermal transformation, followed by air cooling [33].

Austempering is applicable to most medium-carbon steels and alloy steels. Low-alloy steels are usually restricted to 9.5 mm (3/8 in.) or thinner sections, while more hardenable steels can be austempered in sections up to 50 mm (2 in.) thick.

Molten salt baths are usually the most practical for austempering applications. Oils have been developed that suffice in some cases, but molten salts possess better heat-transfer properties and eliminate the fire hazard.

Marquenching. The marquenching (martempering) process is similar to austempering in that the workpiece is quenched rapidly from the austenitizing range into an agitated bath held near the Ms temperature. It differs from austempering in that the workpiece remains at temperature only long enough for the temperature to be equalized throughout the workpiece. When the temperature has attained equilibrium but before transformation begins, the workpiece is removed from the salt bath and air cooled to room temperature. Oils are used successfully for marquenching, but molten salt is usually preferred because of its better heat-transfer properties [33].

Cooling from the marquenching bath to room temperature is usually conducted in still air. Deeper hardening steels are susceptible to cracking while martensite forms if the cooling rate is too rapid. Alloy carburizing steels, which have a soft core, are insensitive to cracking during martensite formation, and the rate of cooling from the Ms temperature is not critical.

Marquenching does not remove the necessity for subsequent tempering. The structure of the metal is essentially the same as that formed during direct quenching [33].

Isothermal quenching is also similar to austempering in that the steel is rapidly quenched through the ferrite and pearlite formation range to a temperature just above Ms. However; isothermal quenching differs from austempering in that two quench baths are employed. After the first quench, and before transformation has time to begin, the workpiece is transferred to a second bath at a somewhat higher temperature where it is isothermally transferred, followed by cooling in air [33].

2.9.2. Tempering.

Tempering of steel is a process in which previously hardened or normalized steel is usually heated to a temperature below the lower critical temperature and cooled at a suitable rate, primarily to increase ductility and toughness, but also to increase the grain size of the matrix. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and also to relieve quenching stresses and to ensure dimensional stability. Tempering usually follows quenching from above the upper critical temperature; however, tempering is also used to relieve the stresses and reduce the hardness developed during welding and to relieve stresses induced by forming and machining [33].

2.9.2. 1. Principal variables affect the microstructure and the mechanical properties.

Variables associated with tempering that affect the microstructure and the mechanical properties of tempered steel include [33].

- Tempering temperature
- Time at temperature
- Cooling rate from the tempering temperature
- Composition of the steel, including carbon content, alloy content, and residual elements

In steel quenched to a microstructure consisting essentially of martensite, the iron lattice is strained by the carbon atoms, producing the high hardness of quenched steels. Upon heating, the carbon atoms diffuse and react in a series of distinct steps that eventually form Fe₃C or alloy carbide in a ferrite matrix of gradually decreasing stress level. The properties of the tempered steel are primarily determined by the size, shape, composition, and distribution of the carbides that form, with a relatively minor contribution from solid-solution hardening of the ferrite. These changes in microstructure usually decrease hardness, tensile strength, and yield strength but increase ductility and toughness [33].

2.3.2.2. Structural changes.

Based on x-ray, dilatometric, and microstructural studies, there are three distinct stages of tempering, even though the temperature ranges overlap [36, 37, 38, and 39].

- Stage I: The formation of transition carbides and lowering of the carbon content of the martensite to 0.25% (100 to 250 °C, or 210 to 480 °F)
- Stage II: The transformation of retained austenite to ferrite and cementite (200 to 300 °C, or 390 to 570 °F)
- Stage III: The replacement of transition carbides and low-temperature martensite by cementite and ferrite (250 to 350 °C, or 480 to 660 °F)

It is well known that temper embrittlement is a property of steel containing the most widely used alloying elements: Cr, Mn, Ni. The temperature range of the occurrence of temper embrittlement is 400-600 °C, and under condition of slow or stepped cooling, embrittlement arises within a shorter time than isothermal holding. A distinguishing feature of temper embrittlement is the intergranular nature of fracture and the consequent higher temperature of the ductile-brittle transition [40].

Temper embrittlement is the result of appearance of transcrystalline (and not intergranular) brittle failure. This is typical of steels with ordinary purity, and only in steels with large phosphorus content (> 0.05-0.1%) is temper embrittlement a consequence of the appearance of sections of brittle intergranular failure [40].

The typical temper brittleness is found not only in low alloy steels quenched to martensite or bainite, but also in normalized and annealed [40].

The real cause of temper embrittlement is segregation on grain boundaries and other interfaces-active additives, like phosphorous, antimony.

In steel alloyed with carbide forming elements (Cr-Mn) the greatest embrittlement effect is obtained by adding phosphorus [40].

The lack of temper embrittlement in simple carbon steel with high C/P ratio is due to the competition between P and C atoms, i.e., by the displacement of the "deleterious" additive (P) by the "useful" one (C) from the grain boundaries, carbon having a larger bond energy with the grain boundary [40].

Temper embrittlement of steel alloyed with Molybdenum depends on their chemical composition (content of P, Mo, Mn, Si).

The least susceptibility to temper embrittlement is found in steels alloyed with 0.7 % Mo with 0.017-0.036% phosphorus [40].

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2.9.2.3. Tempering temperature.

Several empirical relationships have been made between the tensile strength and hardness of tempered steels such that the measurement of hardness is commonly used to evaluate the response of steel to tempering. Figure 2.18 shows the effect of tempering temperature on hardness, tensile and yield strengths, elongation, and reduction in area of a plain carbon steel (AISI 1050) held at temperature for 1 h. It can be seen that both room-temperature hardness and strength decrease as the tempering temperature is increased. Ductility at ambient temperatures is measured by either elongation or reduction in area, increases with tempering temperature [41].

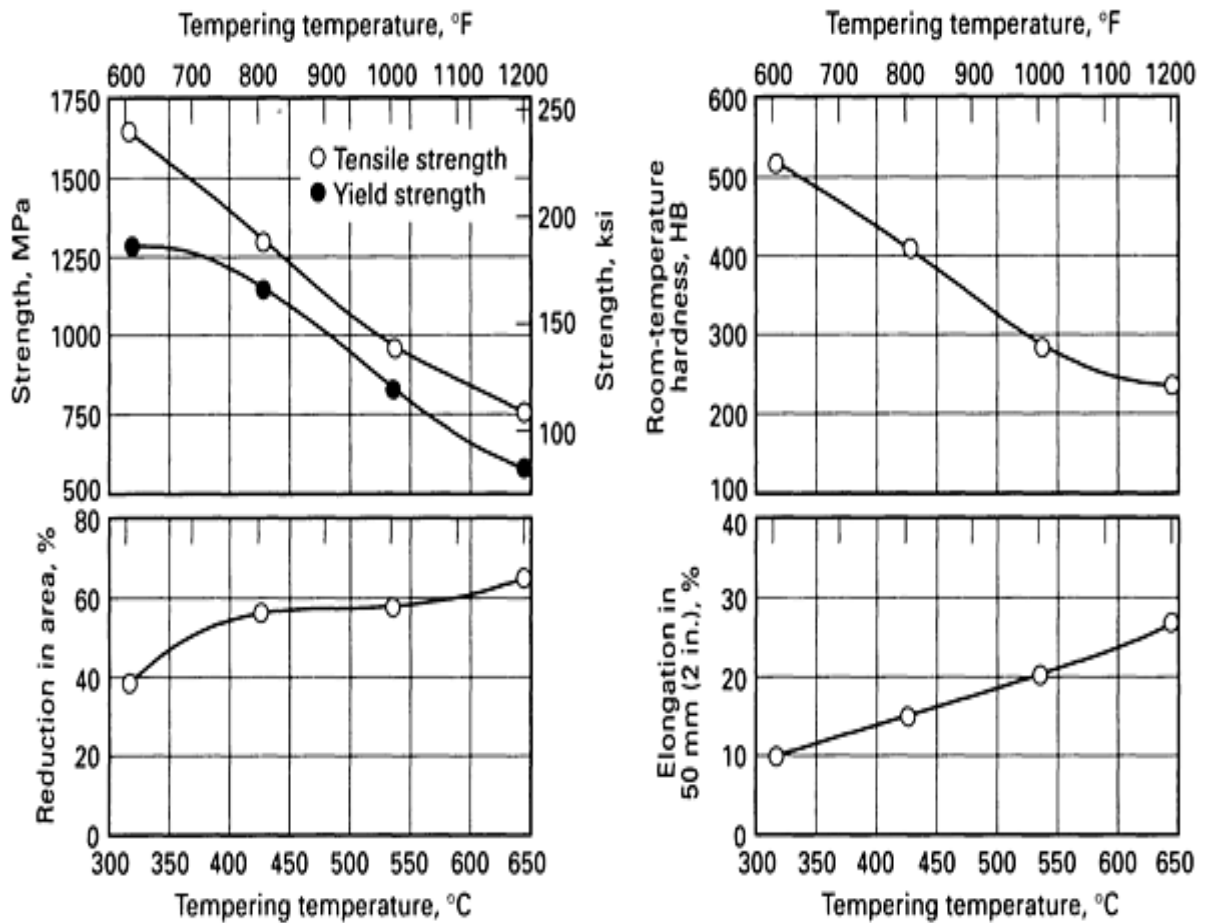


Figure 2.18 Effect of tempering temperature on room-temperature mechanical properties of 1050 steel [33].

Most medium-alloy steels exhibit a response to tempering similar to that of carbon steels. The change in mechanical properties with tempering temperature for 4340 steel is shown in [figure 2.19](#).

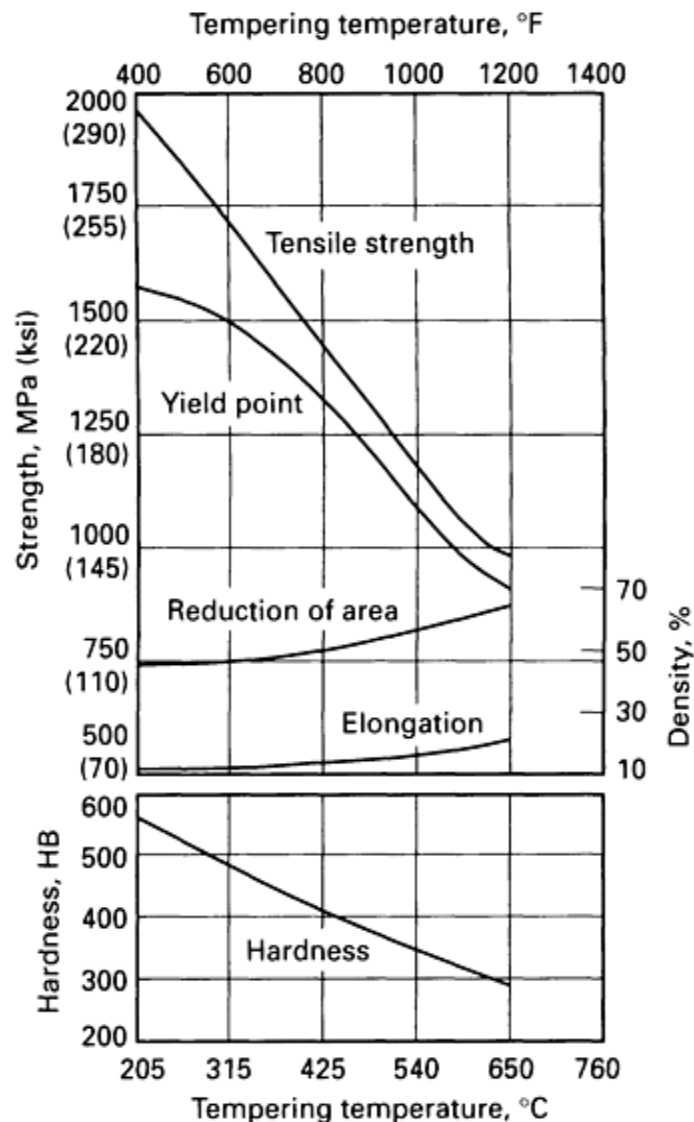


Figure 2.19 Effect of tempering temperature on the mechanical properties of oil-quenched 4340 steel bar [\[42\]](#).

2.9.2.4. Effect of tempering on notch toughness.

There is no decrease in ductility in the temperature range of tempered martensite embrittlement, or TME (also known as 500 °F embrittlement or one-step temper embrittlement) because the tensile tests are performed on smooth, round specimens at relatively low strain rates. However, in impact loading, catastrophic failure may result when alloy steel is tempered in the tempered martensite embrittlement range (260 to 370 °C, or 500 to 700 °F). Additional information is available in the article "Embrittlement of Steels" in Volume 1 of ASM Handbook, formerly 10th Edition Metals Handbook

Whereas elongation and reduction in area increase continuously with tempering temperature, toughness, as measured by a notched-bar impact test, varies with tempering temperature for most steels, as shown in [figure 2.20](#). Tempering at temperatures from 260 to 320 °C (500 to 610 °F) decreases impact energy to a value below that obtained at about 150 °C (300 °F).

Above 320 °C (610 °F), impact energy again increases with increasing tempering temperature. Both plain carbon and alloy steels respond to tempering in this manner. The phenomenon of impact energy minima centered around 300 °C (570 °F) is called tempered martensite embrittlement (TME) or 500 °F embrittlement [33].

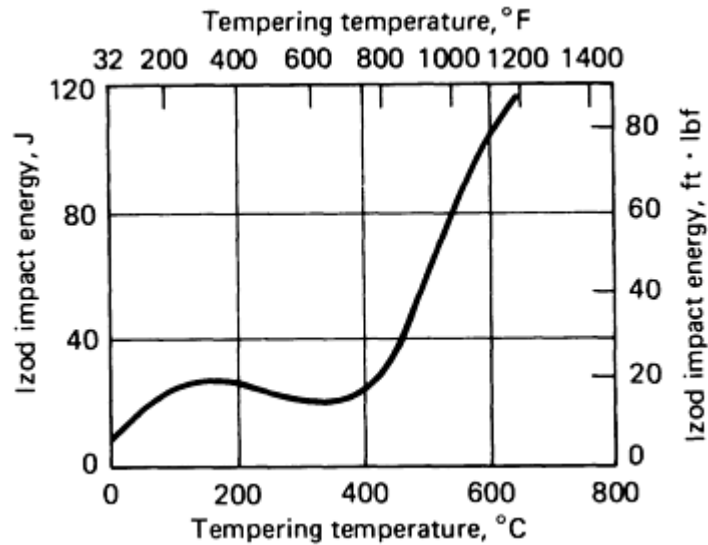


Figure 2.20 Notch toughness as a function of tempering temperature for 4140 (UNS G41400) ultrahigh-strength steel tempered 1 h [33].

2.9.2.5. Cooling rate.

Another factor that can affect the properties of steel is the cooling rate from the tempering temperature.

Although tensile properties are not affected by cooling rate, toughness (as measured by notched-bar impact testing) can be decreased if the steel is cooled slowly through the temperature range from 375 to 575 °C (705 to 1065 °F), especially in steels that contain carbide-forming elements. Elongation and reduction in area may be affected also. This phenomenon is called temper embrittlement and is discussed in the section "Temper Embrittlement" in this article. Additional information is available in the article "Embrittlement of Steels" in Volume 1 of ASM Handbook, formerly 10th Edition Metals Handbook [33].

CHAPTER 3

EXPERIMENTAL WORK

Chapter 3

Experimental Work

3.1. Alloy processing

ASTM A352 consists of many alloys; two alloys only were selected for this study with the following chemical composition shown in table 3.1.

Table 3.1 Chemical Composition according to ASTM A352.

Code	Chemical composition, mass. %							
	C	Si	Mn	P	S	Ni	Cr	Mo
Alloy 1 (LC2)	0.25 max	0.60 max	0.50 - 0.80	0.04 max	0.045 max	2.00 - 3.00
Alloy 2 (LC2-1)	0.22 max	0.50 max	0.55 - 0.75	0.04 max	0.045 max	2.50 - 3.50	1.35-1.85	0.30-0.60

3.1.1. Materials preparation

A hundred kilograms of low carbon steel scrap (0.2%C) was used as a base alloy to process alloy 1. Some alloying elements have been added with the scrap to produce the required chemical composition. These alloying elements are presented in weights at table 3.2.

Table 3.2 Alloying addition in weights for Alloy 1

Alloying elements			
Ferrosilicon	Ferromanganese	Nickel	Scrap
25 Gram	50 Gram	2.5 Kg	97.425 Kg

3.1.2. Melting and casting operations

The scrap was charged into an induction furnace and the alloying elements were added after melting the scrap to ensure homogeneous distribution through the melt. After that, a specimen was taken from the furnace to be analyzed by using A spectro analytical instrument model ARL 3560 (Switzerland) to achieve the chemical composition.

A ferrosilicon powder was applied on the surface of the melting metal at the surface of the induction furnace after one hour and have from the beginning of heating (time taken for melting) in order to make deoxidation to obtain steel with low gases in order to improve the mechanical properties.

The melt was poured into a heated ladle after the temperature reached to 1600 °C, and then pouring the melt from that ladle into a green molding sand (Bentonite) have y block cavity.

The melting induction furnace has the following specifications

- Capacity of 100 Kg.
- Power 100 KW.
- Lining (refractory) (Mg O)[rammed powder + granular magnesia]
- Temperature measurement by using Pt-Pt/Rh electronic thermocouple (type S).

3.1.3. Chemical composition adjustment.

The following chemical composition shown in **table 3.3** was achieved after analyzing the test specimen.

Table 3.3 Chemical composition for alloy 1 during melting

Code	Chemical composition, mass. %							
	C	Si	Mn	P	S	Ni	Cr	Mo
Alloy 1	0.205	0.447	0.533	0.0235	0.0217	2.39

Figure 3.1 also gives a better presentation for the chemical composition shown in table 3.3

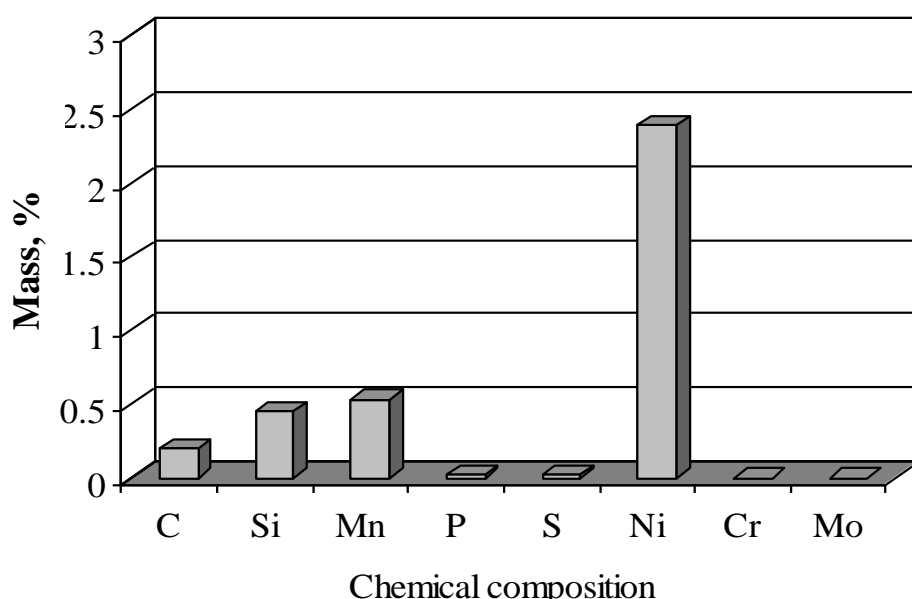


Figure 3.1 Chemical compositions for alloy 1 during melting

From **table 3.3** and **figure 3.1** it is clear that the achieved chemical composition is matched with the composition shown in table 1.1 for alloy 1.

However, it was recommended to increase the amount of Nickel in the melt to be in the range (2.5 - 3 %) to be suitable for alloy 1 as well as alloy 2.

So another amount of Nickel must be added to the melt at the furnace.

A 250 gram of pure Nickel was added to the melt to make balance to achieve alloy1 with the high Nickel content. Another chemical analysis was made by taking another specimen from the melt. Table 3.4 presents the chemical composition of the melt after the addition of Nickel.

Table 3.4 Chemical composition for alloy 1 during melting after Nickel balance

Code	Chemical composition, mass. %							
	C	Si	Mn	P	S	Ni	Cr	Mo
Alloy 1	0.199	0.388	0.574	0.0203	0.015	2.73

Figure 3.2 was drawn for more illustration of the achieved chemical composition shown in **table 3.4**

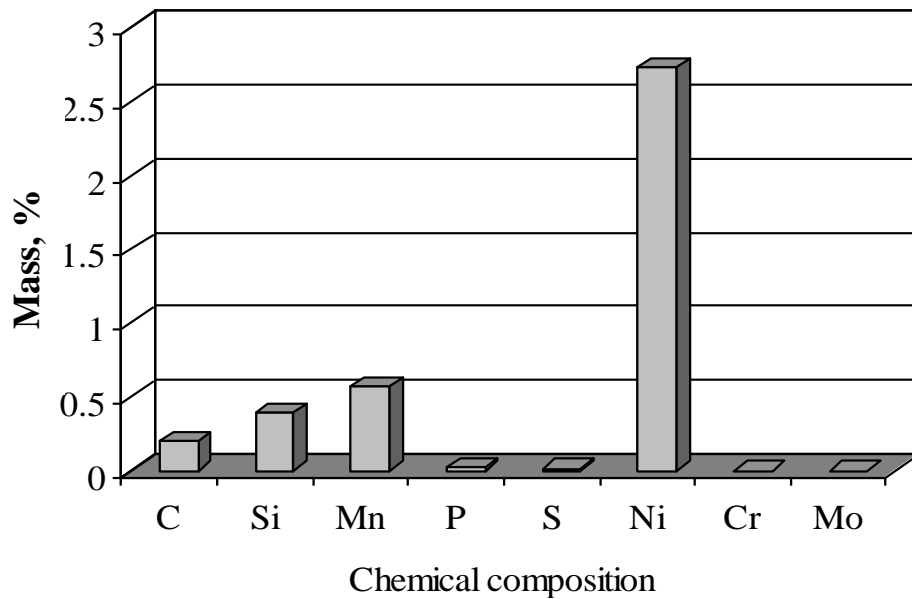


Figure 3.2 Chemical compositions for alloy 1 during melting after Nickel balance

Comparing the data shown in [table 3.3](#) with the achieved data at [table 3.4](#) or the presented data at [figure 3.2](#), it is noticed that the chemical composition of the melt still satisfies alloy 1.

Two Y-blocks were cast from that melt in a Bentonite moulding sand mixture with the following dimensions shown at [figure 3.1](#).

Each Y-block was weighing 20 Kg.

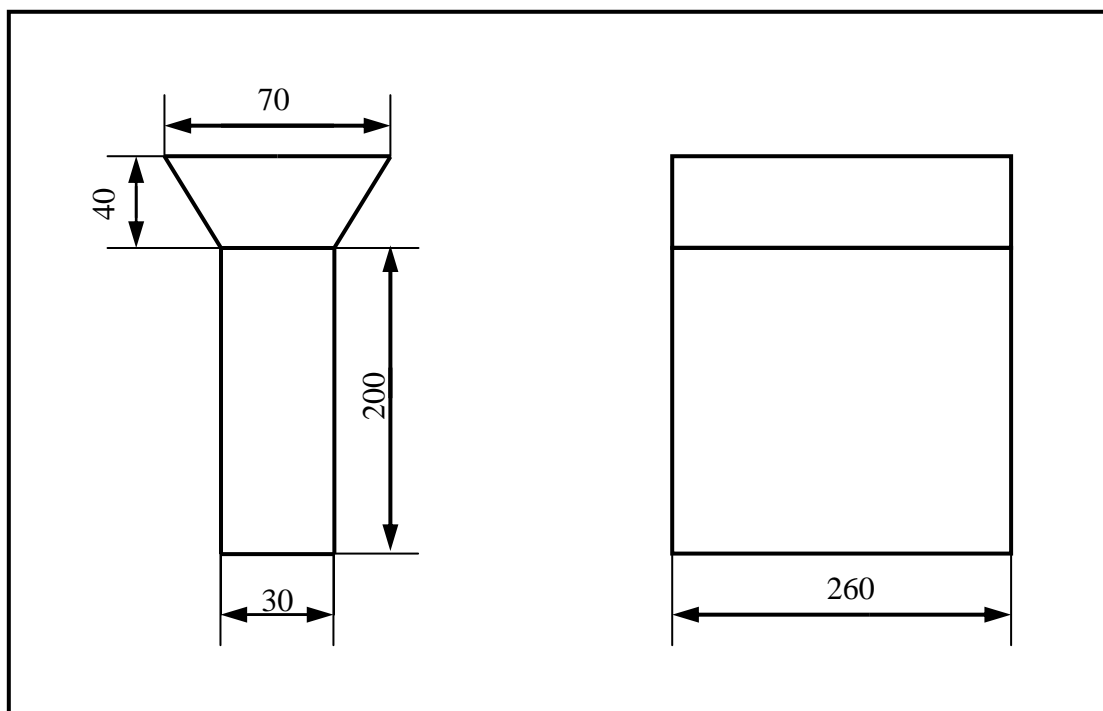


Figure 3.3 Y block dimensions

A modification was made on the rest of the melt (60 Kg) to obtain alloy 2 by adding 1.85 Kg of FeCr and 0.5 Kg of Molybdenum to the melt.

A specimen was taken from the melt for analyzing and the following chemical composition shown in [table 3.5](#) or [figure 3.4](#) was obtained.

Table 3.5 Chemical composition for alloy 2

Code	Chemical composition, mass. %							
	C	Si	Mn	P	S	Ni	Cr	Mo
Alloy 2	0.219	0.448	0.581	0.0265	0.0269	2.82	1.87	0.536

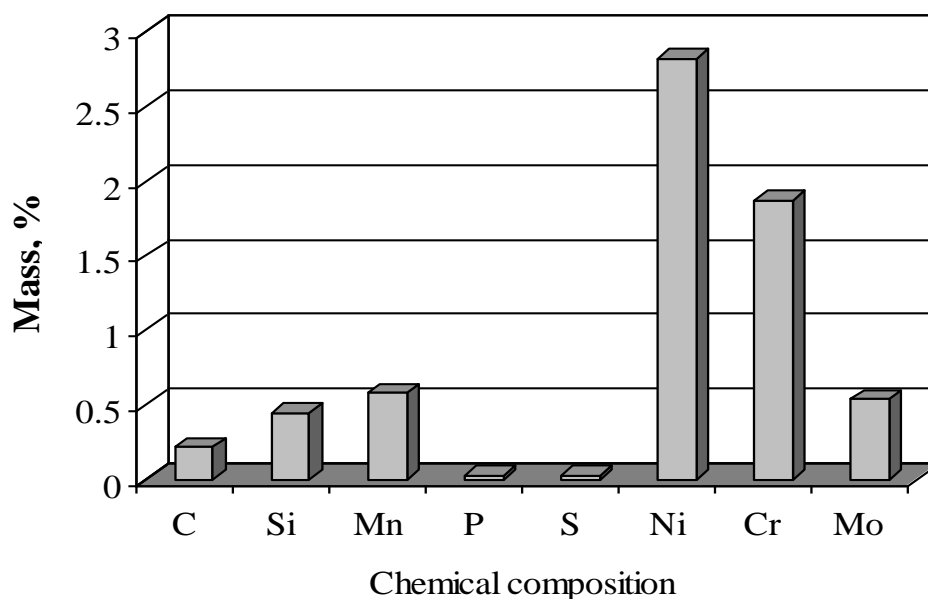


Figure 3.4 Chemical compositions for alloy 2

One Y-block was cast from that melt representing alloy 2.

Further modification was made on alloy 2 by adding an amount of Niobium (10 gram) to the melt. A specimen was taken and a chemical composition was made for it to obtain a new alloy with the chemical composition shown in [table 3.6](#) or [figure 3.5](#).

Table 3.6 Chemical composition for alloy 3

Code	Chemical composition, mass. %								
	C	Si	Mn	P	S	Ni	Cr	Mo	Nb
Alloy 3	0.186	0.392	0.536	0.0223	0.0210	2.74	1.81	0.527	0.0647

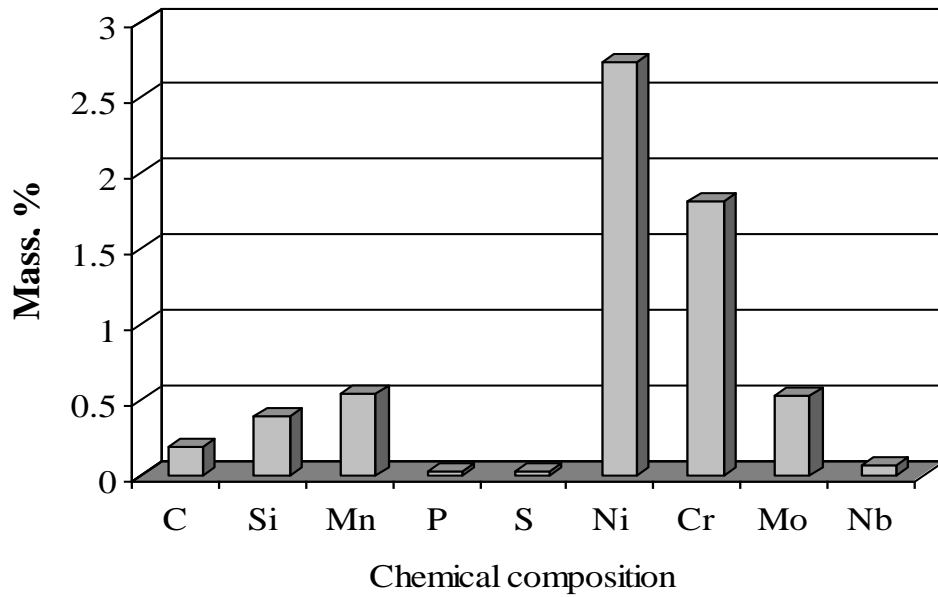


Figure 3.5 Chemical compositions for alloy 3

One more Y-block was cast from alloy 3.

3.2. Test Specimens Preparation

All test specimens must be machined by suitable operations such as cutting, turning, milling, and grinding in accordance with a suitable standard such as American Standard for Testing Materials (ASTM).

3.2.1. Tension test specimens.

The tension test specimens were machined in accordance with specifications of ASTM E-8M.

Figure 3.6 shows the dimensions of the tensile test specimen.

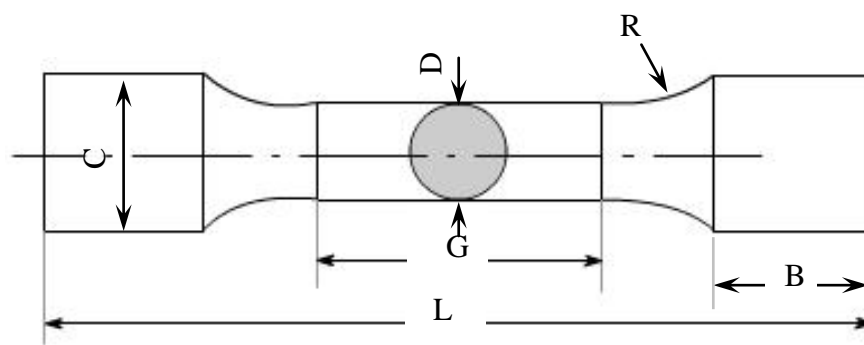


Figure 3.6 Tensile test specimen with circular cross-section

L—Overall length, approximate (145 mm)

G—Gage length (62.5 mm)

B—Length of end section (35 mm)

C—Diameter of end section (20 mm)

D—Diameter (12.5 mm)

R—Radius of fillet, min (10 mm)

3.2.2. Impact test specimens.

Charpy V-Notch samples were prepared in accordance with specifications in ASTM E-23– 02a as shown in the schematic **figure 3.7**.

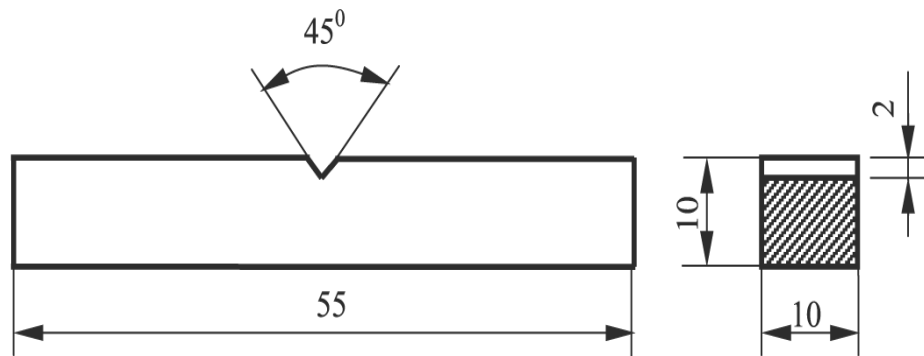


Figure 3.7 Charpy specimen dimensions

3.2.3. Preparation of test specimens for both non metallic inclusions and microstructure.

Samples for microscopic examination were prepared in accordance with standard procedures for metallographic preparation. Each sample was mechanically ground and then coarse polished using progressively finer grades of silicon carbide impregnated emery paper with copious amounts of water as lubricant. This was followed by fine polish to a mirror like surface finish using an alumina-based compound suspended in distilled water. Now the specimen is ready for the non metallic inclusions examination under the optical microscope. The specimens should be chemically etched using a 2 pct nital solution (2% Nitric acid plus 98% Alcohol) for the microstructure investigation. Etching facilitates in revealing grain boundaries, the overall morphology of the grains, and the location and morphology of second-phase particles. The polished and etched samples were examined in an optical microscope at low magnifications and photographs taken using standard bright field illumination.

3.3. Heat Treatment cycle (according to ASTM A352)

Heat treatment is considered as a tool to enhance the mechanical properties of the as-cast steel alloys. In the present study, hardening-tempering cycles are used to develop the targeted properties.

A pit type furnace was used for the applied heat treatment cycles and a built in thermocouple was used in order to measure the temperature raise and give the measured temperature at a digital screen in the control unit.

3.3.1. Hardening

All the mechanically prepared specimens (tensile, impact) were subjected to a hardening heat treatment.

So a quenching heat treatment was made by heating the test specimens to 900 °C (Austenitic temperature) and holding it at that temperature for 45 minutes then oil quenching was made as shown in **figure 3.8**.

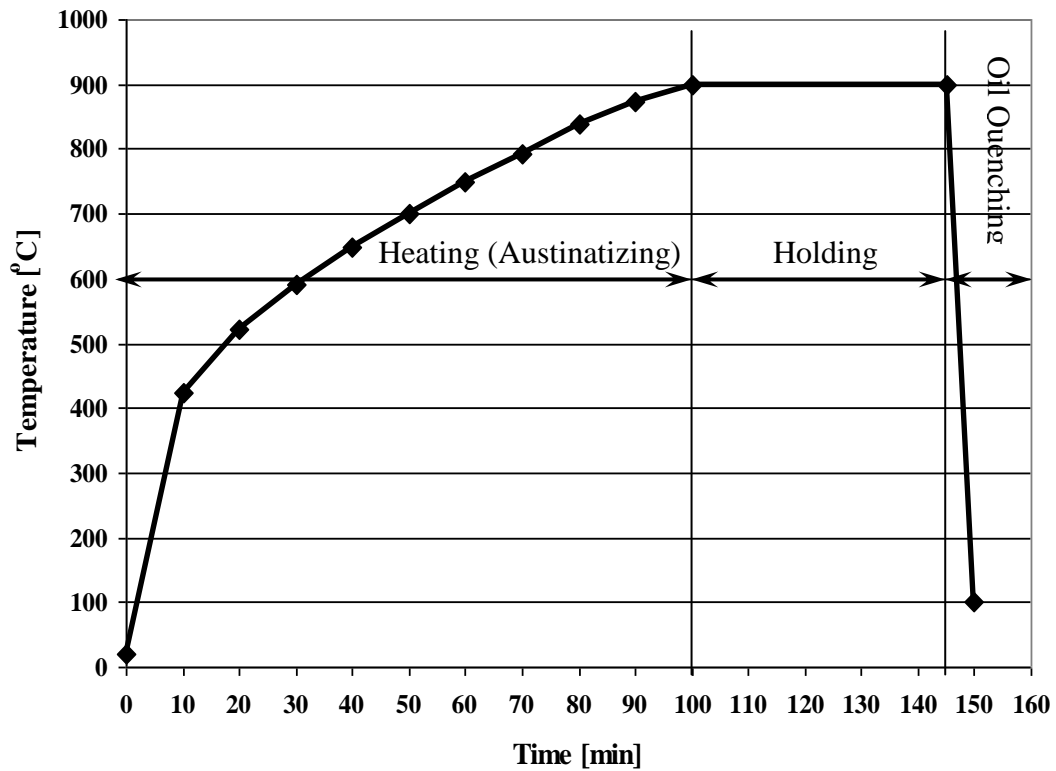


Figure 3.8 Hardening (Heating-Quenching) Heat Treatment cycle

3.3.2. Tempering

Tempering heat treatment is very necessary to improve the mechanical properties and for internal stress relief. It occurs by heating the specimens to 590 °C, then using a holding time suitable to the thickness (one hour for each inch) of the specimens, and then air cooling as shown in figure 3.9.

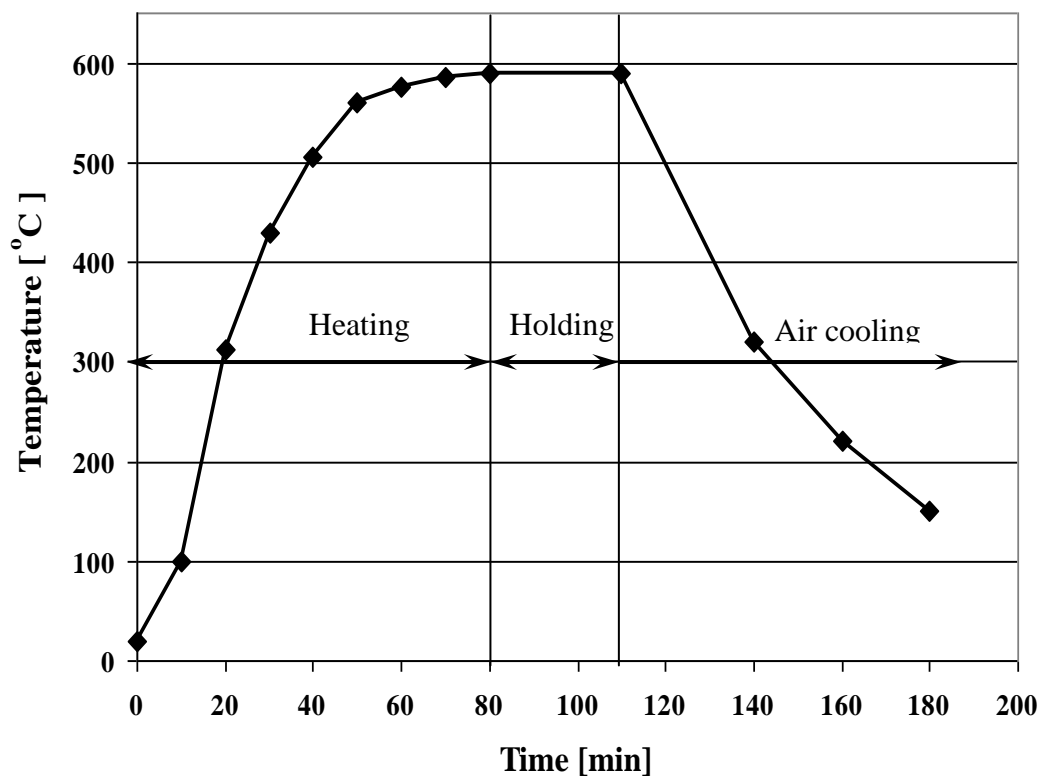


Figure 3.9 Tempering heat treatment

3.4. Evaluation

Mechanical properties of all the prepared alloys must be evaluated to insure that the alloys are suitable to the desired applications such as cast valves which are used in low temperature applications.

3.4.1. Mechanical characterization of the steel alloys.

Characterizations of steel alloys were done by 3 different mechanical testes. The first one is the tensile test which measures the ultimate strength as well as the elongation, the yield strength is considered as 80% of the ultimate tensile strength; where there no clear yield appeared during testing. Impact test is the second important one; it is essentially, where the toughness can be assisted. Hardness is also measured as a final test.

Table 3.7 represents the standard mechanical properties of the two standard grades (LC2&LC2-1) selected for this study from ASTM A352.

Table 3.7 Standard mechanical properties for alloy 1 and alloy 2

Code	Mechanical properties				
	Tensile strength [MPa]	Yield strength [MPa]	Elongation %	Reduction of area %	Impact energy [J] Tested at -73 °C
Alloy 1 (LC2)	485-655	275	24	35	20
Alloy 2 (LC2-1)	725-895	550	18	30	41

3.4.1.1 Tension Test

Tensile tests were carried out using a Zwick 1484 screw-driven machine of 200 KN capacity in displacement control at a crosshead speed of 10 mm/min at a temperatures of 18 °C (room temperature).

3.4.1.2. Impact Test

Charpy specimen shown in **Figure 3.7** is generally oriented such that the root of the notch lies perpendicular to the surface of the component being tested. The orientation (longitudinal or transverse) of the specimen is selected according to the appropriate product specifications. The specimens are held in alcohol (maintain the temperature for long time) for 10 min at the required test temperature by using a special refrigerator and then broken in the Charpy type impact tester.

3.4.1.3. Hardness Test

Rockwell hardness test (HRA) with was done on the surface of test specimens before and after the heat treatment to see the effect of the heat treatment cycle.

The Rockwell hardness test method consists of indenting the test material with a diamond cone or hardened steel ball indenter. The indenter is forced into the test material under a preliminary minor load F_0 (**Figure 3.10 A**) usually 10 kgf. When equilibrium has been reached, an indicating device, which follows the movements of the indenter and so responds to changes in depth of penetration of the indenter is set to a datum position. While the preliminary minor load is still applied an additional major load is applied with resulting increase in penetration (**Figure 3.10 B**). When equilibrium has again been reach, the additional major load is removed but the preliminary minor load is still maintained. Removal of the additional major load allows a partial recovery, so reducing the depth of penetration (**Figure 3.10 C**). The permanent increase in depth of penetration,

resulting from the application and removal of the additional major load is used to calculate the Rockwell hardness number.

$$HR = E - e$$

F_0 = preliminary minor load in kgf

F_1 = additional major load in kgf

F = total load in kgf

e = permanent increase in depth of penetration due to major load F_1 measured in units of 0.002 mm

E = a constant depending on form of indenter: 100 units for diamond indenter, 130 units for steel ball indenter

HR = Rockwell hardness number

D = diameter of steel ball

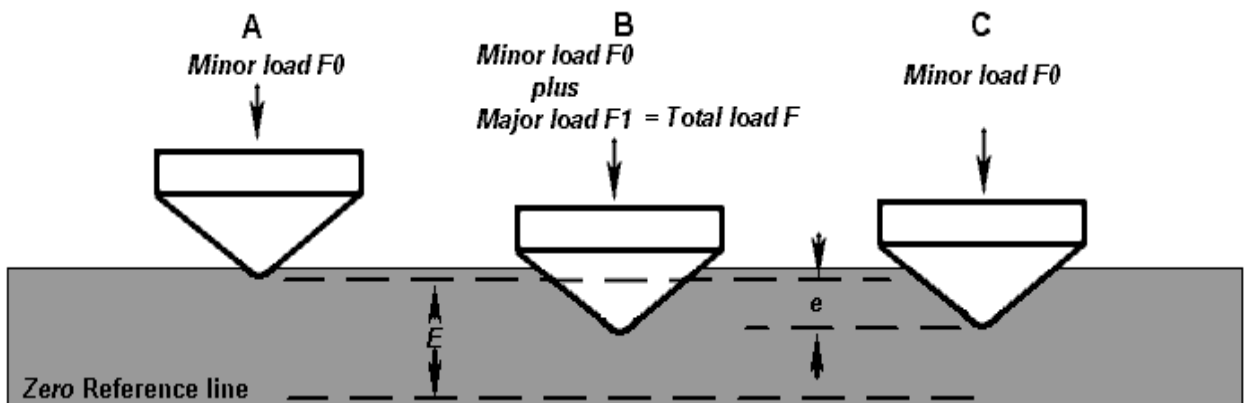


Figure 3.10 Rockwell Principle

Table 3.8 Rockwell Hardness Scales

Scale	Indenter	Minor Load F_0 kgf	Major Load F_1 kgf	Total Load F kgf	Value of E
A	Diamond cone	10	50	60	100
B	1/16" steel ball	10	90	100	130
C	Diamond cone	10	140	150	100

Typical Application of Rockwell Hardness Scales

HRA Cemented carbides, thin steel and shallow case hardened steel

HRB Copper alloys, soft steels, aluminum alloys, malleable irons, etc.

HRC Steel, hard cast irons, case hardened steel and other materials harder than 100 HRB

CHAPTER 4

RESULTS AND DISCUSSION

Chapter 4

Results and Discussion

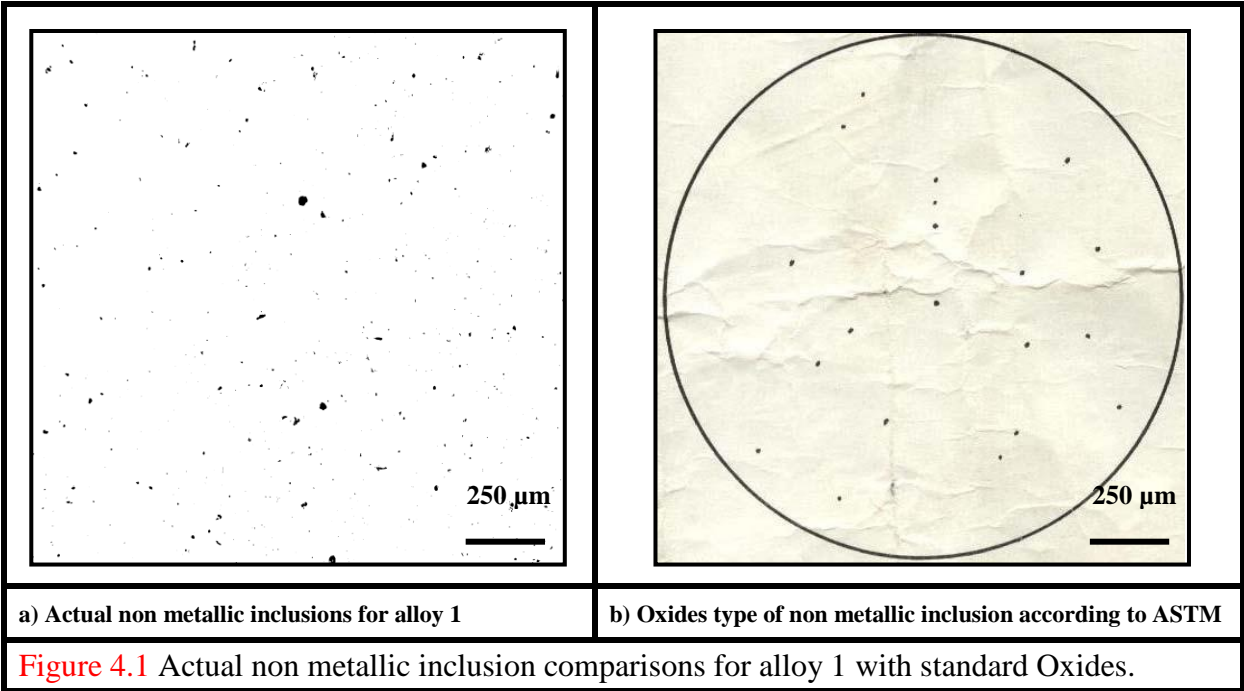
4.1. Investigation of alloy 1

Non metallic inclusions content, microstructure investigation, and mechanical properties like strength, toughness and hardness were investigated.

4.1.1. Non-metallic Inclusion Assessment for alloy 1

The amount, distribution, size and chemical composition of non-metallic inclusions have a direct influence on the steel properties [28].

Non metallic inclusion micrograph of alloy 1 is presented in figure 4.1



Comparing the micrograph in figure 4.1 (a) with the standard shown in figure 4.1 (b) (according ASTM), it is clear that alloy 1 contains oxides type grade D-2.5-Heavy

It is clear that the non metallic inclusions for alloy 1 that indicated in figure 4.1 are fine, distributed, and homogeneous which would not deteriorates the mechanical properties.

The negative effect of non metallic inclusions can be avoided by controlling its size, and distribution to eliminate the negative effect on the mechanical properties [28].

4.1.2. Microstructure Investigation for alloy 1.

4.1.2.1. As Cast Microstructure

The microstructure shown in **figure 4.2** contains martensite matrix with some ferrite aggregates. This microstructure is a heterogeneous microstructure which would lead to low mechanical properties, consequently a suitable heat treatment cycle like quenching and tempering is required in order to make a homogeneous microstructure with better mechanical properties.

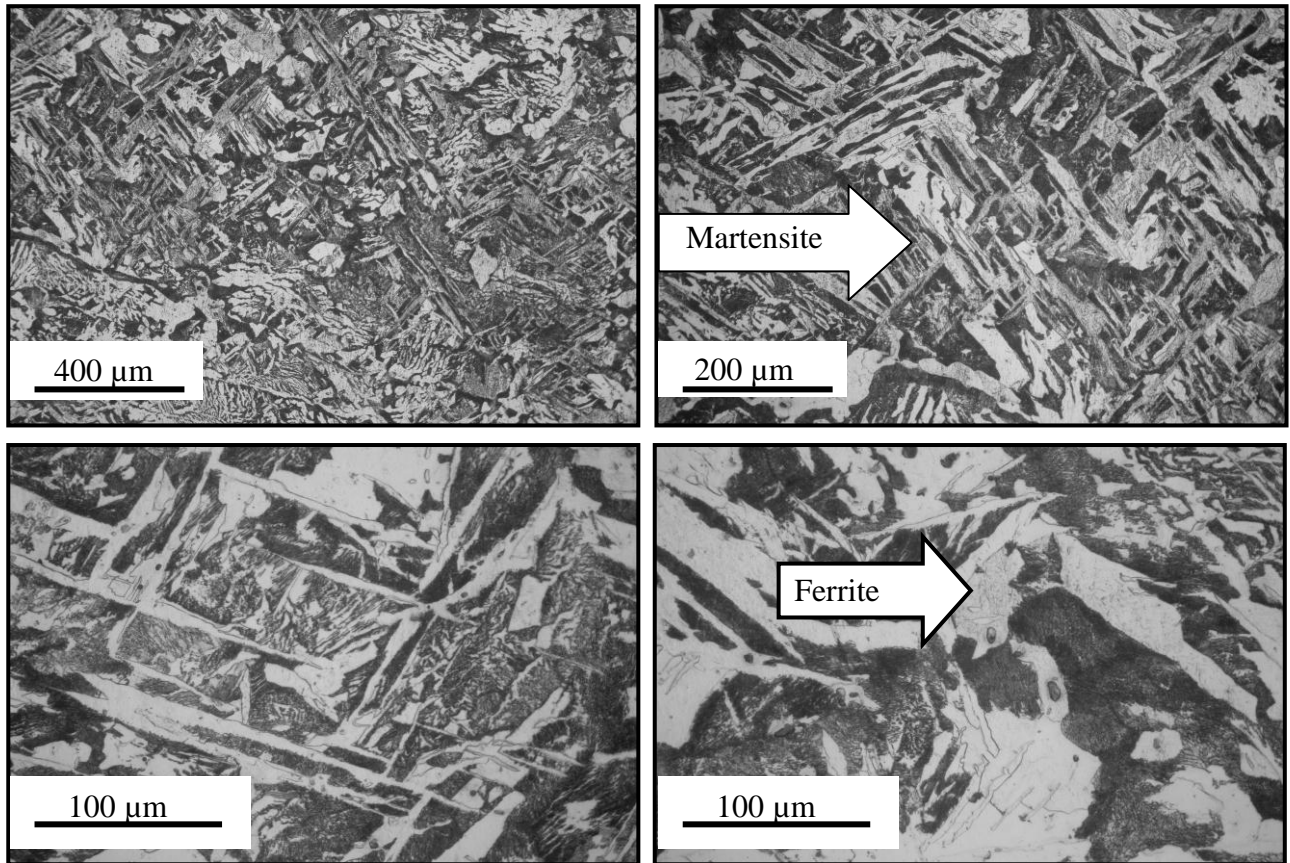


Figure 4.2 The as cast microstructure for alloy 1 with different magnifications

4.1.2.2. Heat treated Microstructure

Figure 4.3 represents the microstructure of alloy 1 after being subjected to hardening and tempering heat treatment cycle.

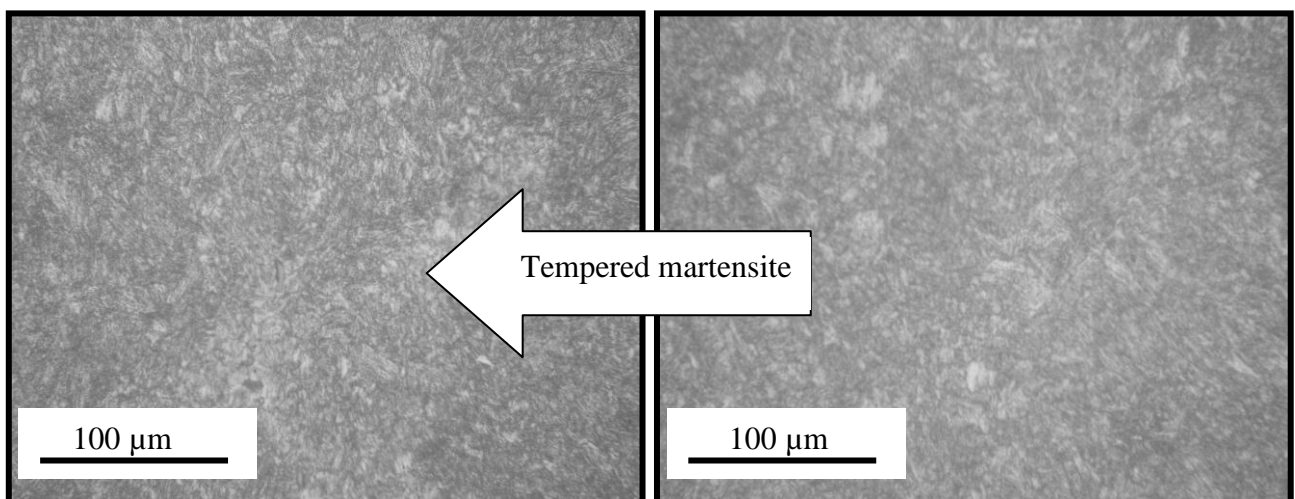


Figure 4.3 Microstructure for Alloy 1 after heat treatment

Quenching process distributed the ferrite portion through the micro structure to form hard martensite phase which is relatively brittle, so the tempering process is done in order to produce less brittle martensite (Tempered martensite) and to relief the internal stresses that occurred during quenching. The microstructure became homogeneous and fine after heat treatment cycle which would lead to high mechanical properties [33].

4.1.3. Mechanical properties evaluation for alloy 1

Engineers are most interested in the way in which metals will respond to the application of external forces. Engineers are dealing with the elastic and plastic behavior, as well as the over-all strength and fracture characteristics of materials. Mechanical properties such as hardness, strength, and toughness are measured for this alloy as follows.

4.1.3.1. Hardness test results

Hardness usually implies a resistance to deformation or resistance to indentation.

The hardness test results are shown in Table 4.1.

Table 4.1 Hardness test results for alloy 1.

Alloy	condition	Specimen number									Mean [HRA]
		1	2	3	4	5	6	7	8	9	
		Rockwell hardness number [HRA]									
Alloy 1	As Cast	51.9	51.1	50.8	49.8	48	47.7	47	45.8	45.7	48.6
	Heat Treated	58.1	58.5	57.7	58.8	57.3	57.6	58.9	56.5	58.7	58

The hardness of the all specimens under testing was increased after the heat treatment operation. The hardness of alloy 1 is increased by 9.4 [HRA]. So the heat treatment cycle (hardening – tempering) has better significant effect on hardness.

Figure 4.4 confirms the good effect of heat treatment on hardness.

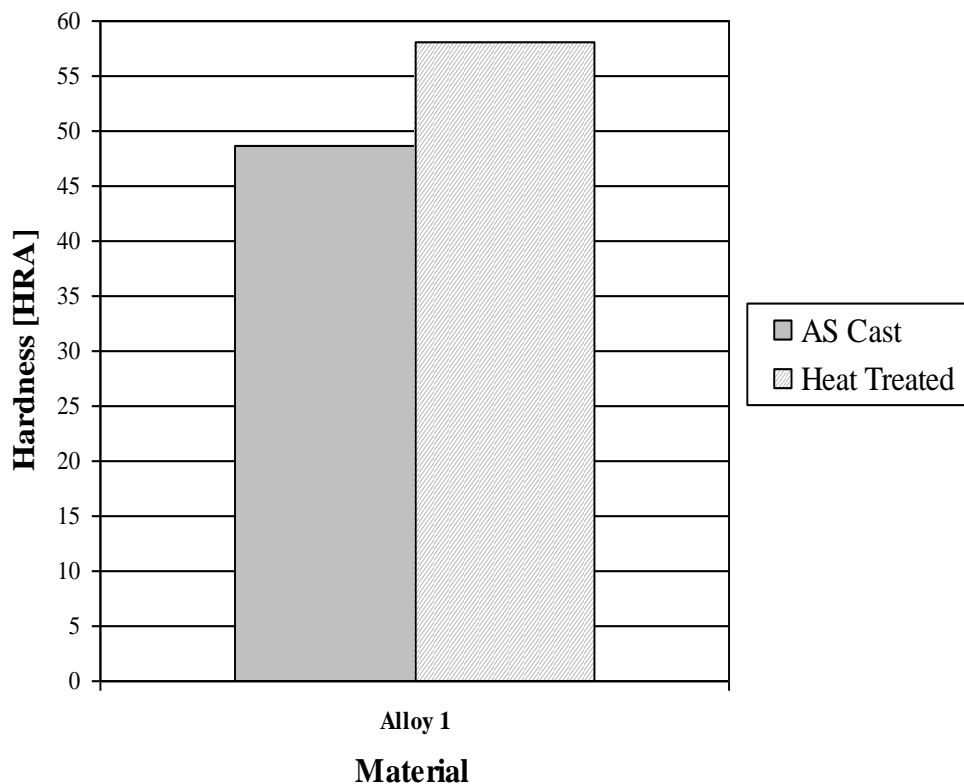


Figure 4.4 Hardness results for alloy 1

4.1.3.2. Tensile test results

Specimens were tensile tested from each alloy before and after the heat treatment. The ultimate tensile strength (UTS) can be clearly calculated whereas the yield is considered as 0.80% of the ultimate tensile strength.

Table 4.2 presents the actual tensile test properties of alloy 1 for the as cast and heat treated conditions.

Table 4.2 Tensile properties for alloy 1

Alloy	Condition	Specimen number	Tensile mechanical properties	
			UTS [MPa]	Mean UTS [MPa]
Alloy 1	As cast	1	468.79	466.9
		2	464.97	
		3	466.83	
	Heat treated	1	616.56	603.9
		2	592.70	
		3	602.43	

the tensile properties presented in figure 4.5 for the as cast and heat treated conditions confirm what have been obtained from the hardness measurements ensuring that the heat treatment cycle was proper selected, the present results are in agreement with the results obtained from the ASTM A352 standard. The improvement of the mechanical properties which is accompanied by the heat treatment cycle is attributed to the homogenous and fine microstructure.

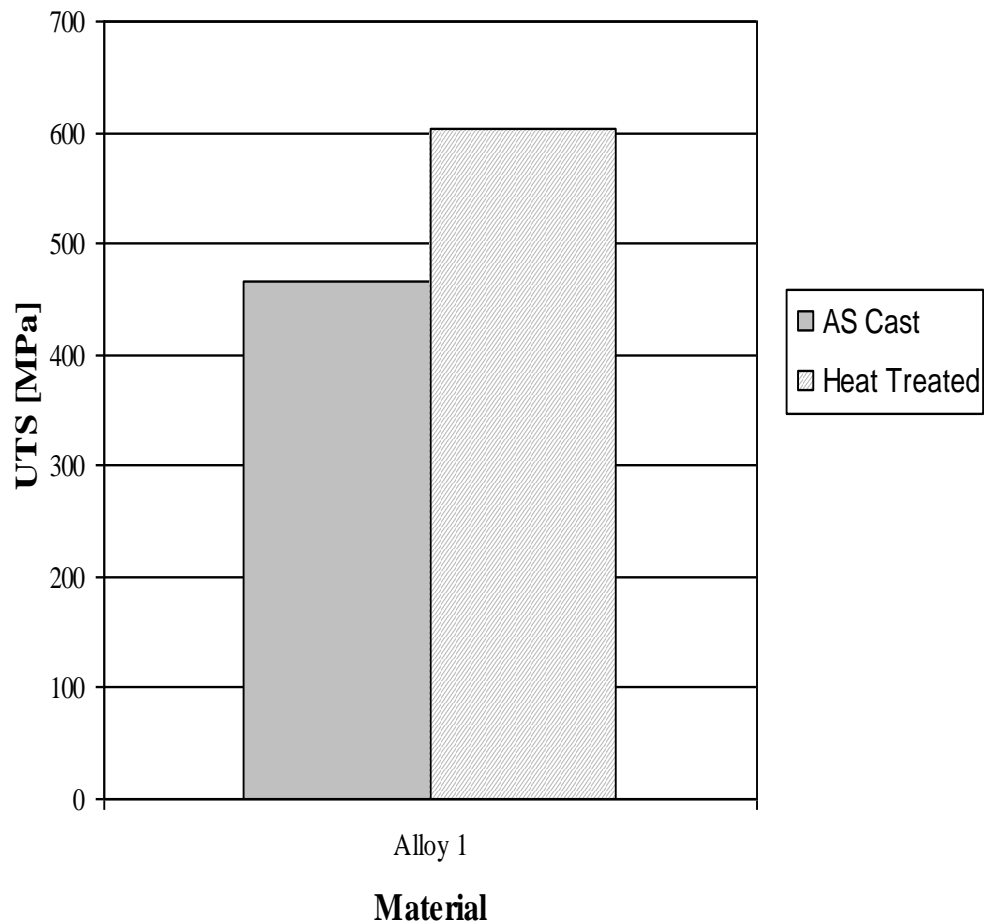


Figure 4.5 Tensile test results for alloy

4.1.3.3. Impact test results

The energy values presented at the following tables are the mean of three test specimens at least to insure that the values are matched with each others.

All specimens are marked with suitable code to be able to identify each one after testing to make the fractographic investigation.

Impact values before and after heat treatment at different subzero temperatures for alloy 1 are presented in [table 4.3](#).

Table 4.3 Impact properties for Alloy 1

Condition	Test temperature [°C]	Mean energy value [J]
As Cast	Room temp. (27 °C)	17.2
	-20	8.9
	-40	7.3
	-60	5
	-73	4.4
Heat Treated	Room temp. (27 °C)	61.5
	-20	54.8
	-40	42.8
	-60	38.4
	-73	25.2

The data included in [table 4.3](#) is presented in [figure 4.6](#) for as cast and heat treated conditions.

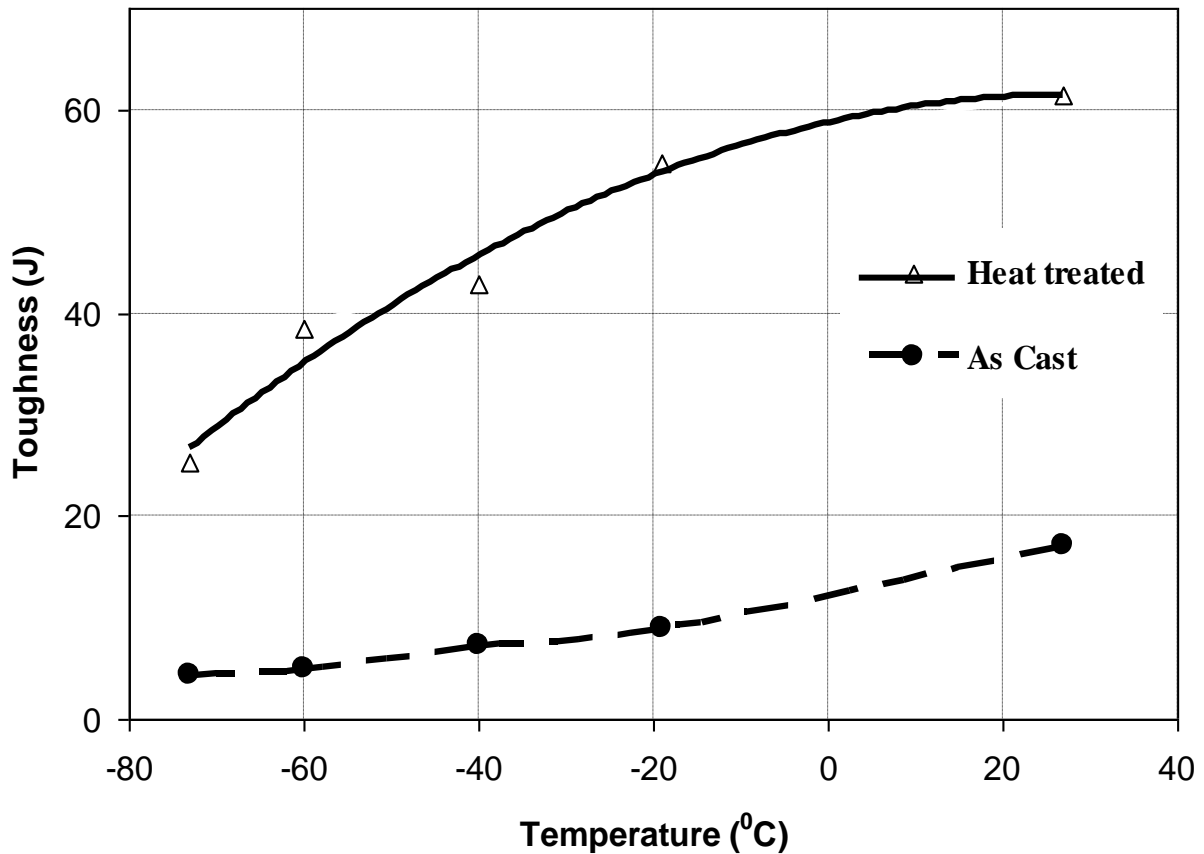


Figure 4.6. Impact toughness for alloy 1 before and after heat treatment.

It is clear that the impact value at room temperature for the as cast conditions has lower value (17.2 J) than that of heat treated condition (61.5 J). This is clearly reflecting the successful effect of heat treatment cycle and confirms what have been concluded previously [33].

On the other hand, it is observed that toughness decreased continuously with the decreasing of testing temperature for both conditions.

Further more the toughness of the heat treated condition is always higher than the as cast condition which is another positive effect of the heat treatment cycle.

Generally, when the ambient temperature drops, the toughness of materials also decrease and it becomes very low at a certain low temperature. This is called cold brittleness, and the temperature at which the material turns from a tough state to a brittle state is called the ductile–brittle transition temperature [4].

Steel castings that have been quenched and tempered have higher notch toughness than similar castings in the as cast conditions [10].

4.1.4. SEM Fractographic Investigation for alloy 1

Fracture surface of impact specimens give the right guide to the investigation whether the material followed ductile behavior or brittle behavior during the testing conditions.

4.1.4.1. As Cast SEM Fractographic Investigation

Fracture surfaces of the dynamically deformed and failed samples were examined in a scanning electron microscope (SEM) so as to determine the macroscopic fracture mode, and to concurrently characterize temperature influences on fine-scale topography. Figure 4.7 (a-b) illustrates the fracture surface of impact specimen at different magnifications for the as cast state tested at room temperature.

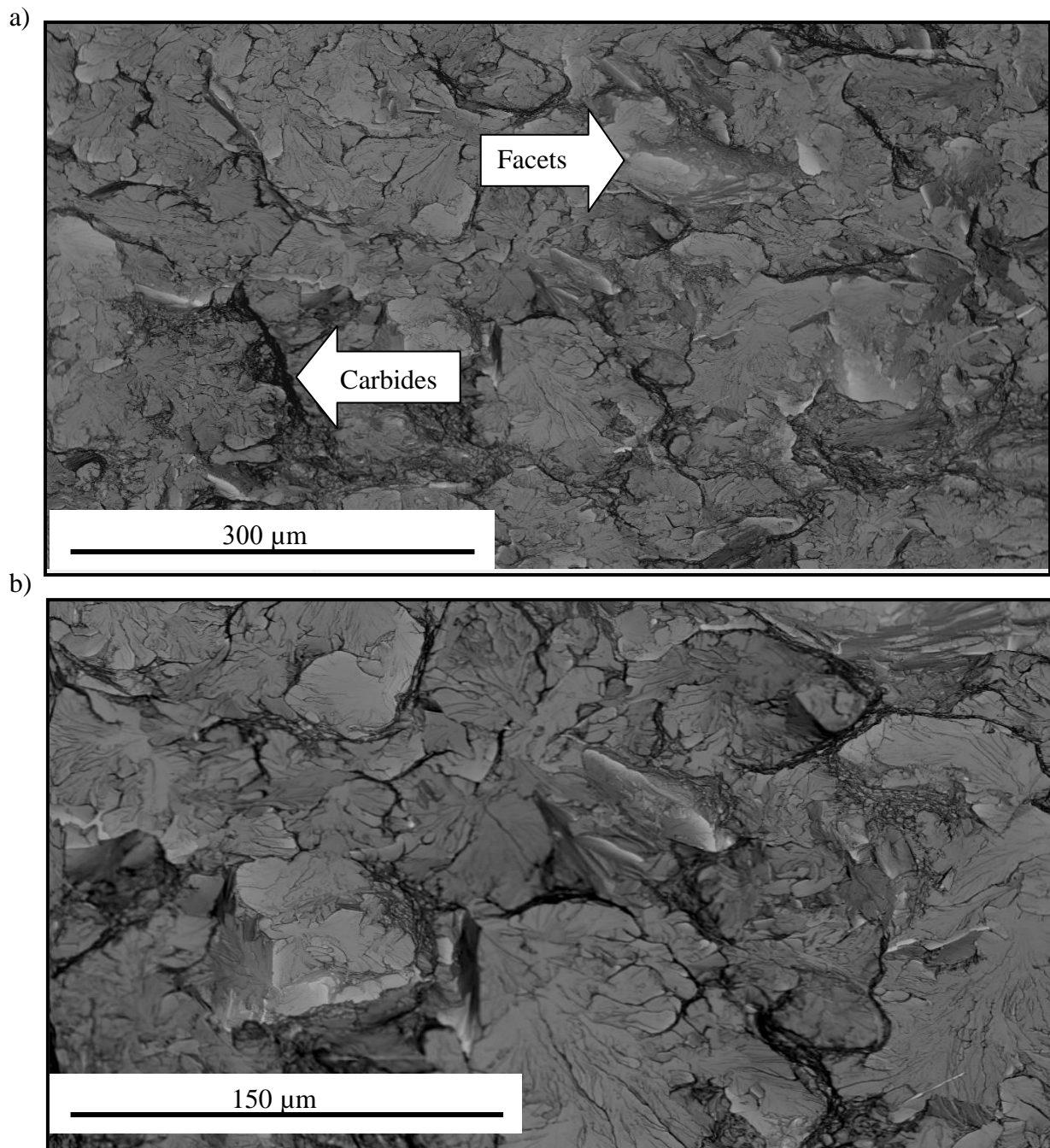


Figure 4.7 (a-b) SEM Fractographic for Alloy 1 at Room Temperature for as cast state.

A vast majority of the fracture surface is cleavage facets with thin layers of carbides imbedded between the facets. This fracture pattern reflects the low value of toughness at the room temperature; the fracture patterns confirm the impact as well as the other mechanical testing results.

For more detecting of the embedded carbide phase, high magnification [X 1500] was taken on the fracture surface as indicated by figure 4.8. It is noticeable that the carbide layer has a continuous feature determining the impact properties and some dimples appeared with facets.

The continuous carbide film forms net-like shape, which facilitates the crack propagation.

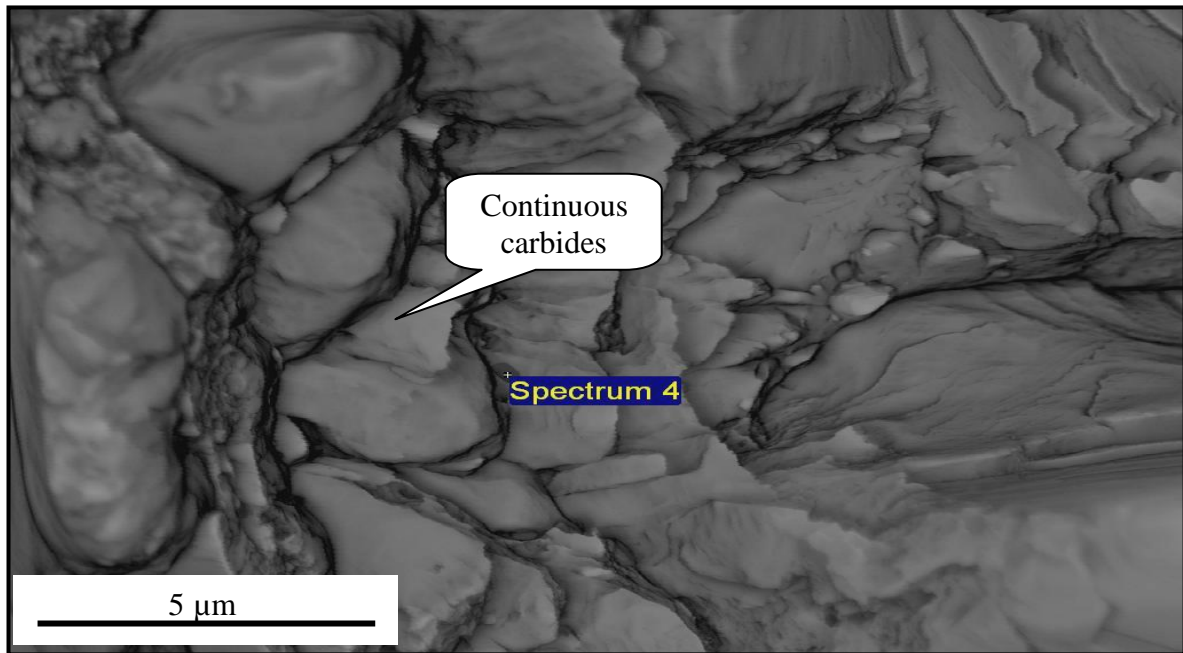


Figure 4.8 SEM for Alloy 1 at Room Temperature in as cast stat with high magnification

For more details an investigation on the fracture surface, XRD qualitative analysis was applied on the imbedded carbide.

Figure 4.9 and table 4.4 represents the XRD chart and qualitative chemical contents of the carbide layer. It can be summarized that the alloy contains iron carbide which is brittle.

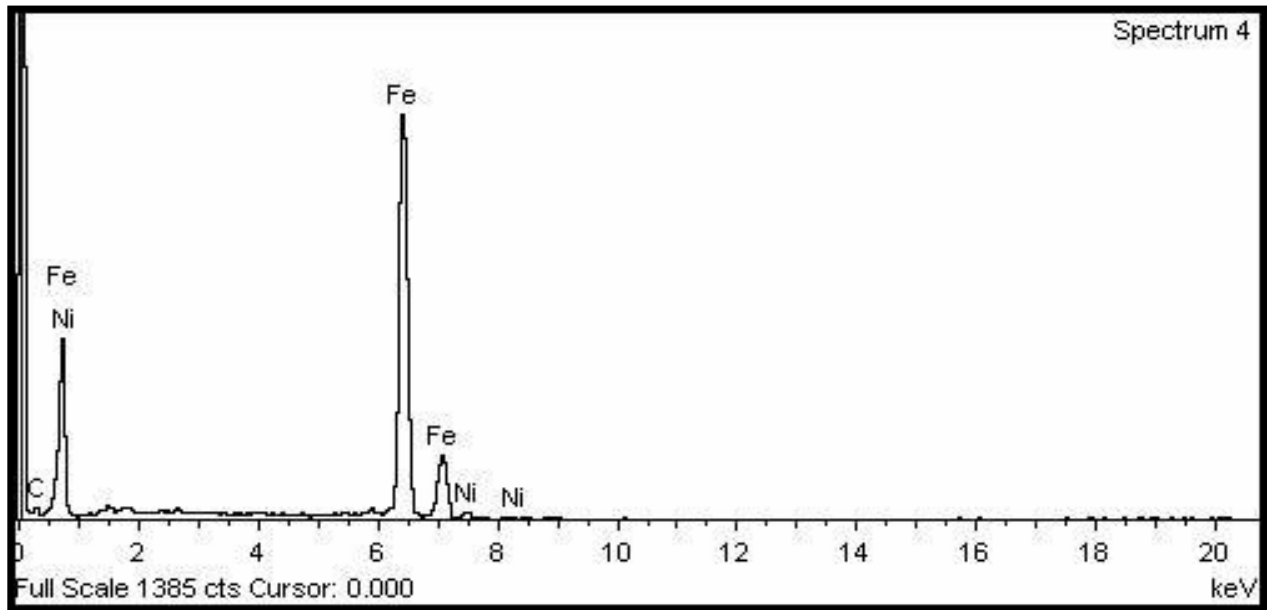


Figure 4.9 XRD for Alloy 1 before heat treatment (as cast)

Table 4.4 XRD Analysis for Alloy 1 before heat treatment (as cast)

Element	C	Fe	Ni
Weight%	6.31	91.26	2.43
Atomic%	23.86	74.26	1.88

Figure 4.10 illustrates the fracture surface for impact specimens tested at -60°C .

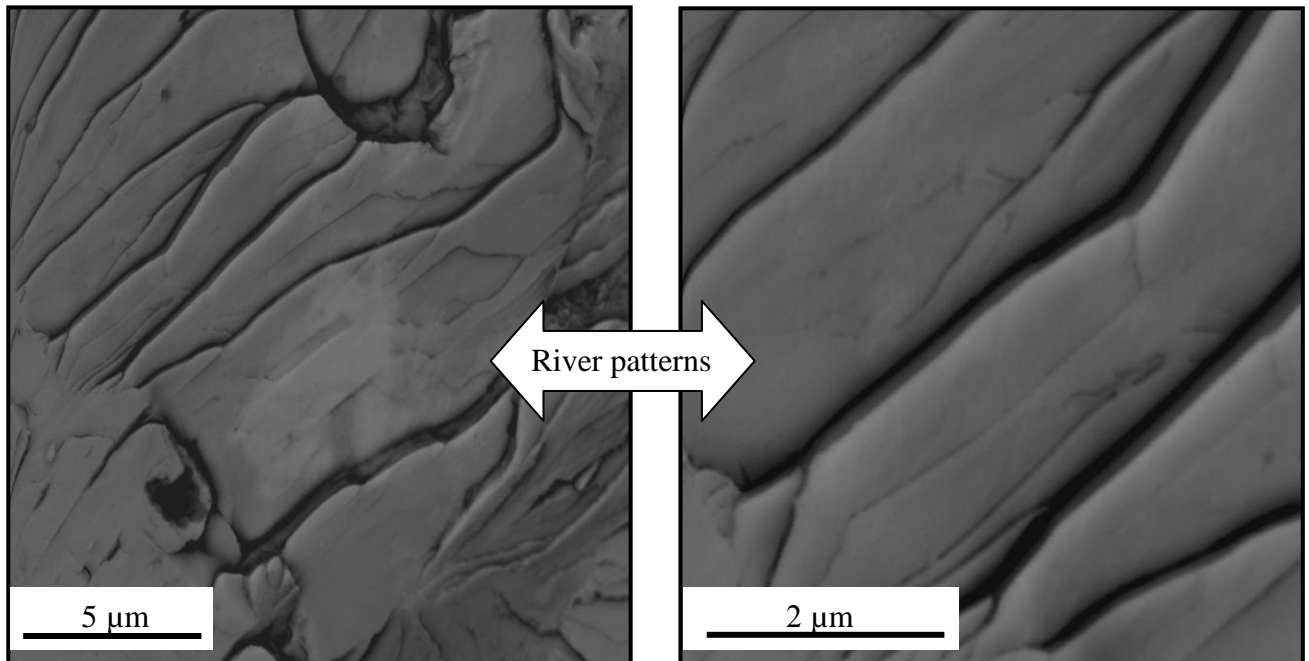


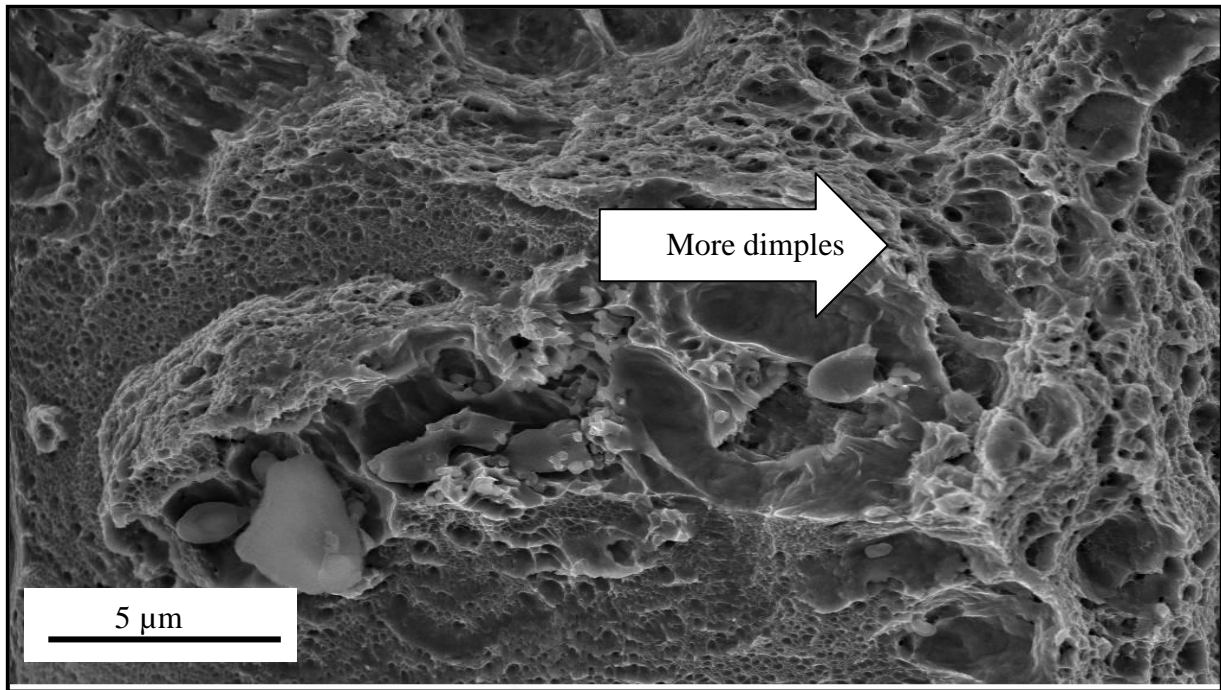
Figure 4.10 SEM Fractographic for Alloy 1 at -60°C at different magnifications for the as cast state.

Both graphs show river pattern fracture. The impact results will be highly decreased as a result of lowering the testing temperature.

4.1.4.2. Heat treated SEM Fractographic Investigation

Heat treatment processes are considered as a powerful tool to improve and develop better mechanical properties.

The fracture surface of a quenching-tempering impact specimen at room temperature is presented in [figure 4.11](#).



[Figure 4.11](#) SEM Fractographic for Alloy 1 at Room Temperature after heat treatment

The fracture surface becomes dimples rupture farther more, it becomes fine dimples which reflect the increasing of toughness after the applied heat treatment cycles.

However, there are some carbide tracing concentrated at the route of that dimples forming troughs.

It is obvious that the fracture mode is changed from brittle facets with imbedded continuous carbide to ductile fine dimples. The fractograph confirms the positive value added by the heat treatment where these fine dimples show more ductility [\[33\]](#).

It is beneficial to look on the fracture heat treated specimens at lower temperature than room temperature to expect the effect of low temperature on the heat treated alloy 1.

Figure 4.12 represents the fracture mode of heat treated alloy 1 at -40°C .

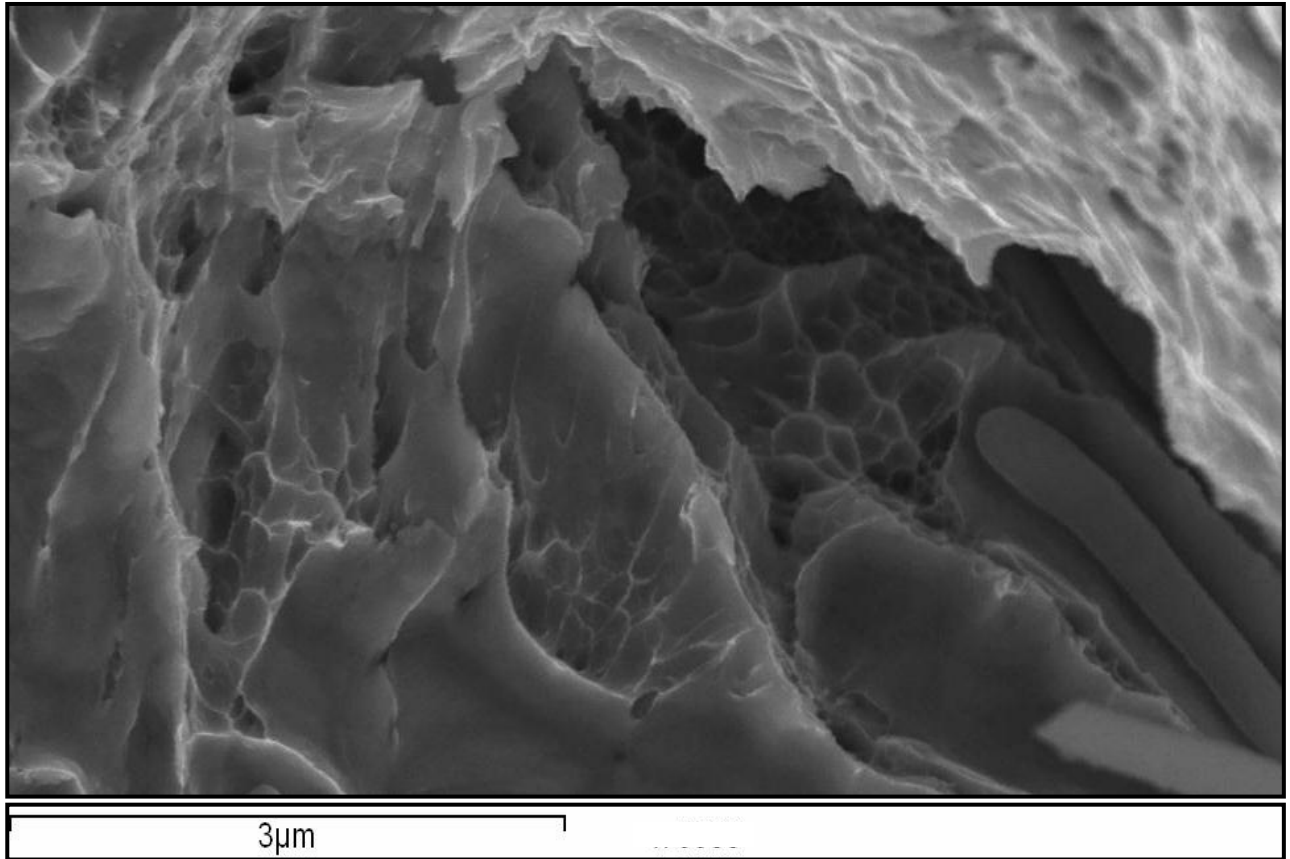


Figure 4.12 SEM fractographic for Alloy 1 at -40°C after heat treatment

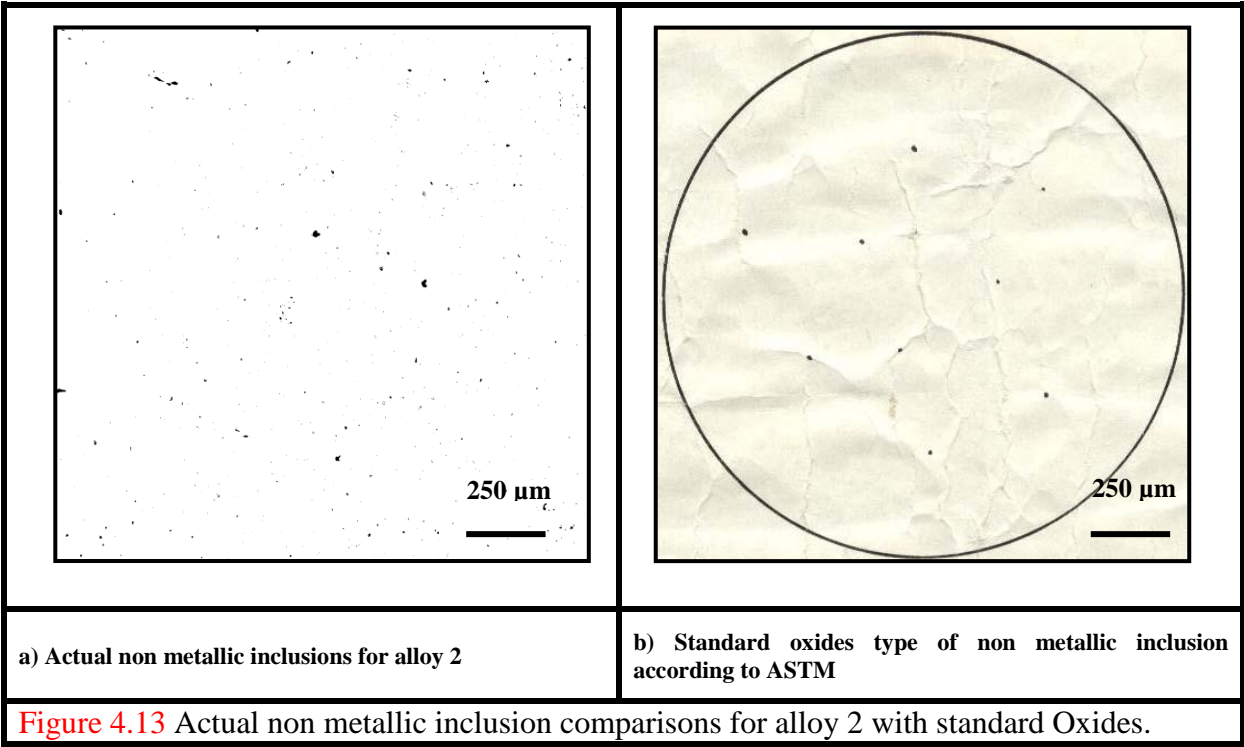
The fracture mode goes towards brittle behavior, as the micrograph changed from complete fine dimples at room temperature to mixture of dimples with considerable amount of facets. However, the present condition does not mean high brittle steel behavior. The dimples portion determines the ductility level.

4.2. Investigation of alloy 2

Chromium and molybdenum were added to the rest of the melt in order to obtain higher strength than that achieved by the conventional alloy 1. Recently, a work published on TMS 2010 confirms that addition of both elements increase strength by making benefit of solid solution hardening and precipitation hardening [43].

4.2.1. Non metallic inclusions in alloy 2.

Figure 4.13 represents the actual non metallic inclusion of alloy 2 compared with the standard oxide of ASTM.

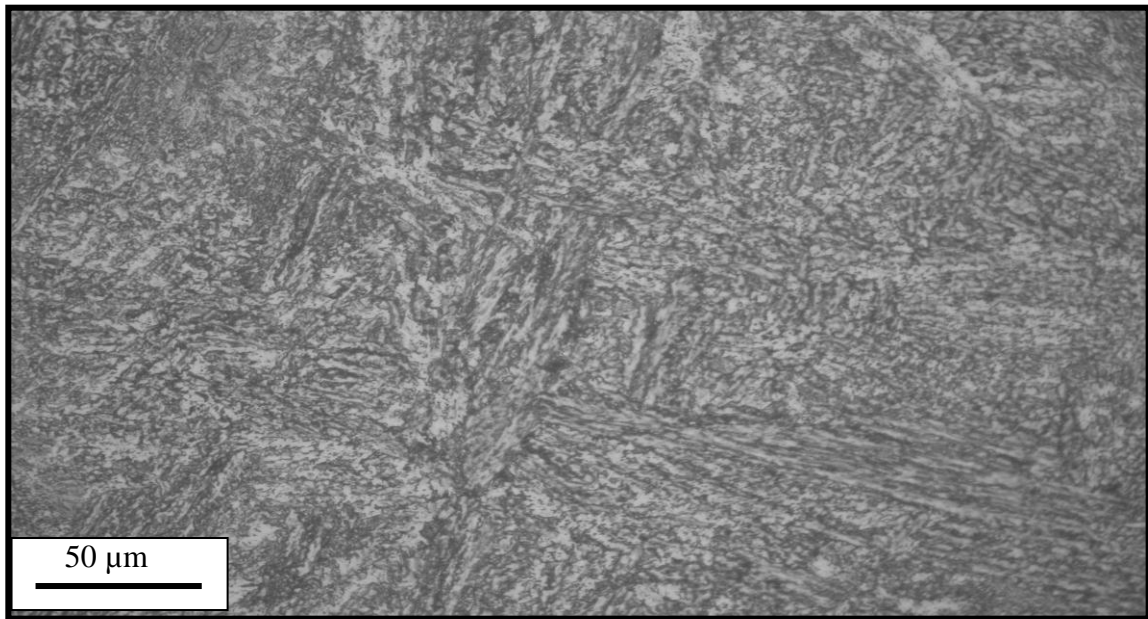


The composition reveals that non metallic inclusions in this alloy are Oxides of grade D-1.5-T, which are not highly harmful and accepted. The non metallic inclusions are thin and homogenously distributed. The mechanical properties are slightly affected by these inclusions [28].

4.2.2. Microstructure Investigation for alloy 2.

4.2.2.1. As cast microstructure

After etching the as cast specimen with 2 pct nital (2% Nitric acid plus 98% Alcohol), microstructure of alloy 2 can be clearly shown in [figure 4.14](#).

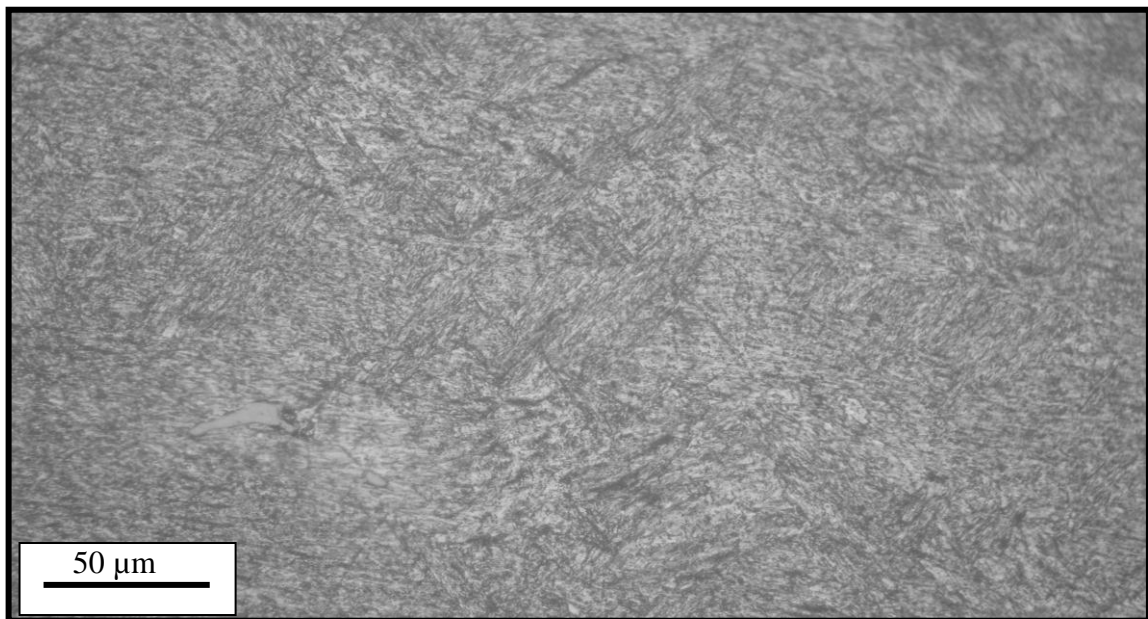


[Figure 4.14](#) the as cast Microstructure for Alloy 2

A very fine martensitic structure shown in [figure 4.14](#) results due to the early forming of Molybdenum carbide (Mo_3C) and Chromium carbide (Cr_3C) during solidification as it was confirmed by reference [\[43\]](#), these carbides are working as nuclei or seeds which would lead to more fine martensitic grains.

4.2.2.2. Heat treated Microstructure

A heat treatment cycle (quenching-tempering) has been applied on the developed alloy 2 for comparison between alloy 1 and alloy 2.



[Figure 4.15](#) Microstructure for Alloy 2 after heat treatment

The heat treated microstructure is slightly finer than in the as cast state, so from [figure 4.14](#) and [figure 4.15](#) there is no significant effect in the microstructure after the heat treatment..

4.2.3. Mechanical properties evaluation for alloy 2

4.2.3.1. Hardness test results

[Table 4.5](#) contains hardness values measured on alloy 2 in the as cast and heat treated conditions. Farther more, the main values of hardness are presented in [figure 4.16](#).

Table 4.5 Hardness test results for alloy 2.

Alloy	condition	Specimen number									Mean [HRA]
		1	2	3	4	5	6	7	8	9	
		Rockwell hardness number [HRA]									
Alloy 2	As Cast	67.3	66.6	66.4	66	65.8	65.4	64.5	63.8	61.7	65.3
	Heat Treated	66.4	65.7	66.8	66.7	67.4	66.4	65.9	65.8	66.1	66.4

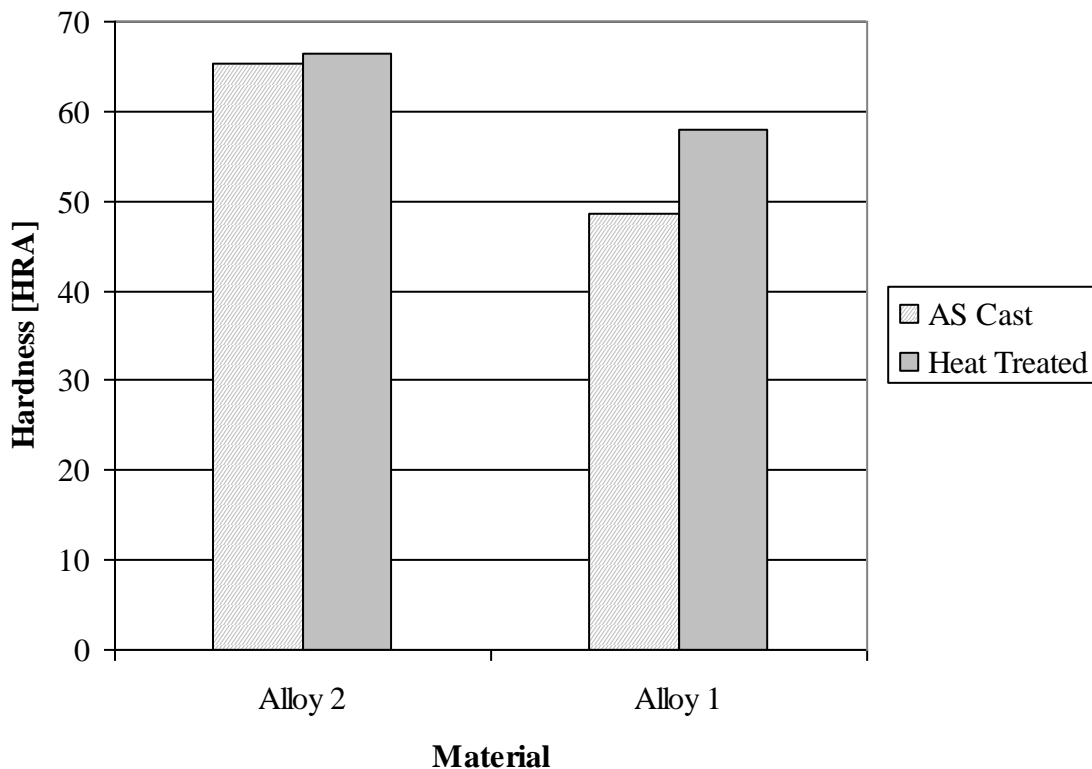


Figure 4.16 Hardness test results for alloy 2 compared with alloy 1

Hardness was increased by a non significant value which indicates that the heat treatment was not effective as in alloy 1.

From the comparison between the hardness results of alloy 1 and the investigated alloy 2, it is clear that the hardness results increased from 48.6 HRA in alloy 1 to 65.3 HRA in the second alloy 2 in the as cast state due to the addition of Chromium and Molybdenum, Which was recently confirmed by the work published in TMS 2010 [43].

4.2.3.2. Tensile test results

The engineering tension test is widely used to provide basic design information on the strength of materials.

Tabulated tensile results are indicated in [table 4.6](#) for both as cast and heat treated states of alloy 2. Mean ultimate strength is illustrated in [figure 4.17](#). It is clear that strength was not increased but it is incremental decrease which confirms that the commercial heat treatment cycle (quenching-tempering) was not recommended. In some other work published [\[11\]](#), it was recommended to carry out tempering at 650 °C and aging for 64 hours at 425 °C.

Table 4.6 Tensile properties for alloy 2

Alloy	Condition	Specimen number	Tensile mechanical properties	
			UTS [MPa]	Mean UTS [MPa]
Alloy 2	As cast	1	911.46	903.4
		2	903.18	
		3	895.56	
	Heat treated	1	860.70	846.55
		2	846.55	
		3	832.40	

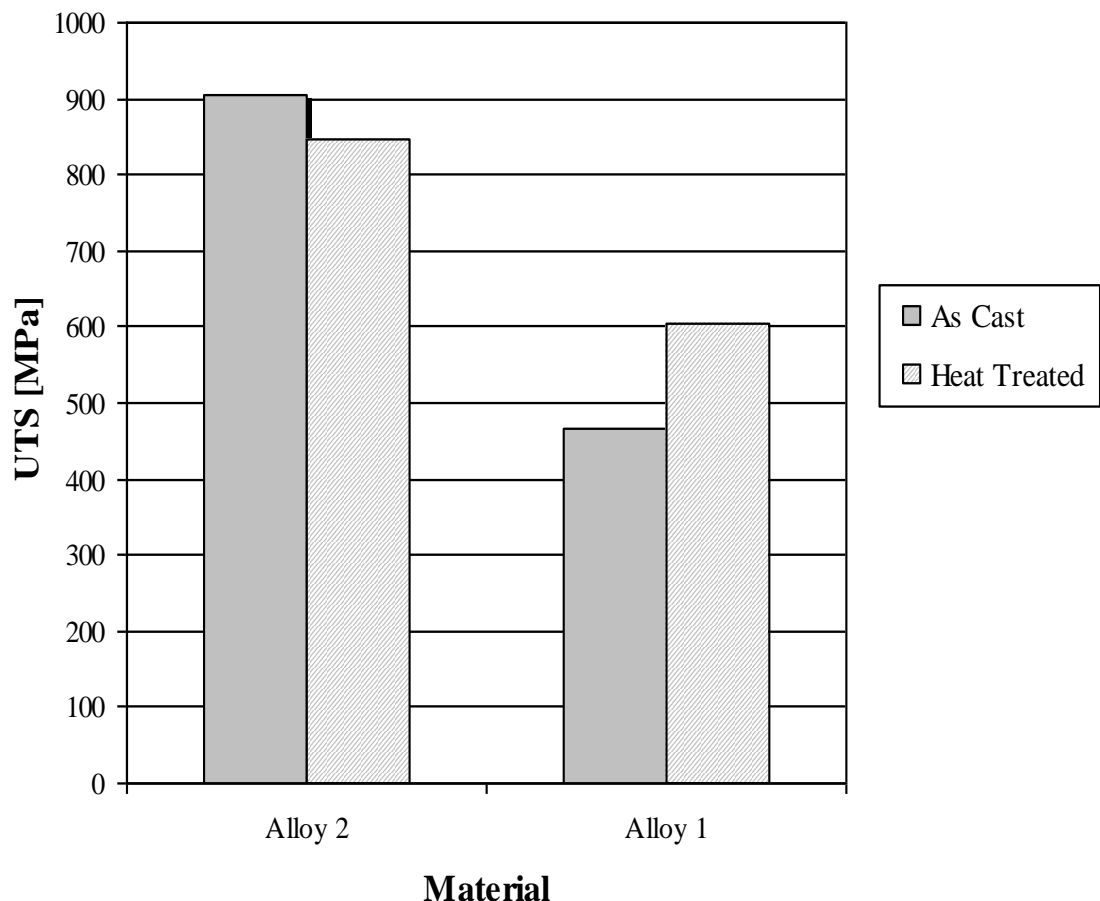


Figure 4.17 Tensile test results for alloy 2 compared with alloy 1

The comparison between the ultimate results of alloy 2 and alloy 1 clearly confirms the positive effect of Chromium and Molybdenum addition in raising the strength of alloy 2.

4.2.3.3. Impact test results

The impact tests have been carried out at different temperatures. The impact results are also tabulated and presented in [table 4.7](#) and [figure 4.18](#).

Table 4.7 Impact properties for alloy 2

Condition	Test temperature [°C]	Mean energy value [J]
As Cast	Room temp. (27 °C)	13.2
	-20	8.9
	-40	7.35
	-60	6.25
	-73	5.2
Heat Treated	Room temp. (27 °C)	13
	-20	10.2
	-40	5.3
	-60	4
	-73	3.8

It was noticed that the impact values after heat treatment cycle changed positively at the region of temperature from 27 [°C] to -30 [°C].

The heat treatment has a negative effect on the impact values at the other region (from -30 °C to -73 °C) as shown in [figure 4.18](#).

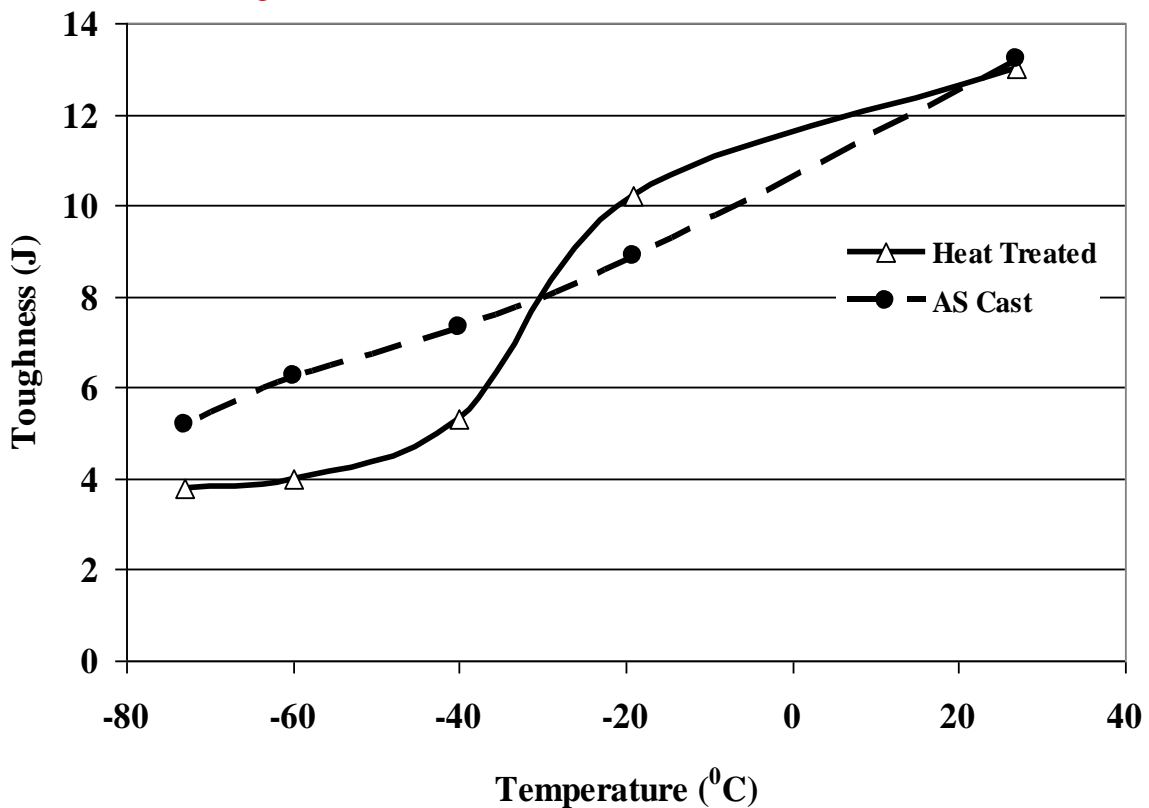


Figure 4.18 Impact toughness results for alloy 2 before and after heat treatment

Obviously, the inadequate heat treatment accelerates the ductile- brittle transition temperature (ITT) at about -30 °C.

The impact results comparison between the investigated alloy 2 and alloy 1 is presented in figure 4.19.

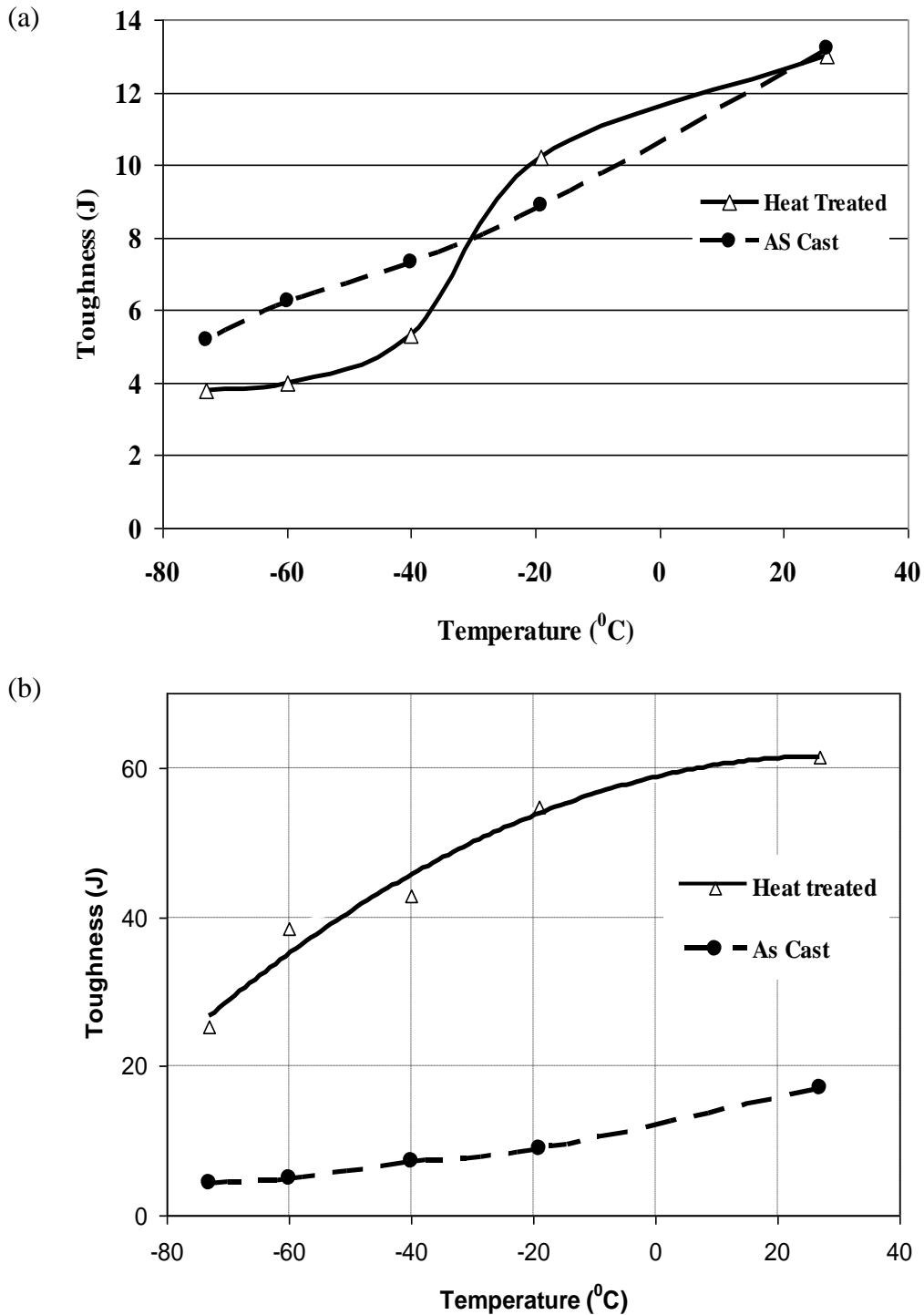


Figure 4.19 (a) Actual impact results of alloy 2 (b) Actual impact results of alloy 1

The impact results of the as cast stat are nearly identical for both alloys. Contrary the impact values of alloy 1 are higher than that of alloy 2 after the heat treatment cycle. The previous results emphasis that the quenching-tempering heat treatment cycle is necessary for alloy 1 and not recommended for alloy 2 [11].

4.2.4. SEM Fractographic Investigation for alloy 2

Fracture surface are considered as an accreditation of the measured mechanical properties.

4.2.4.1. As Cast SEM Fractographic Investigation

Figure 4.20 represents the fracture of impact test specimen tested at room temperature. The fracture surface shows coarse dimples rupture and continuous carbide film impeded between this dimples. Dimples reflect the impact value at room temperature and the continuous impeded carbide film reflects also the low impact value at that temperature.

A qualitative x-ray analysis (XRD) has been performed on the carbide film. Figure 4.20 contains the XRD pattern and table 4.8 includes the peak values of the containing elements. The XRD pattern states that Chromium carbide was found.

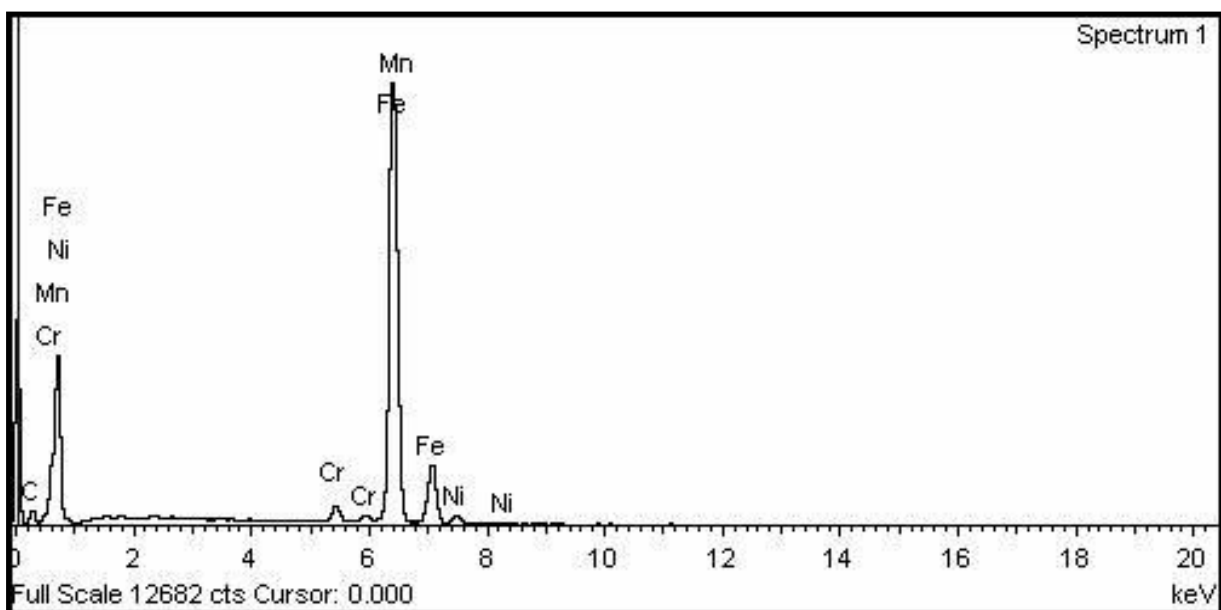
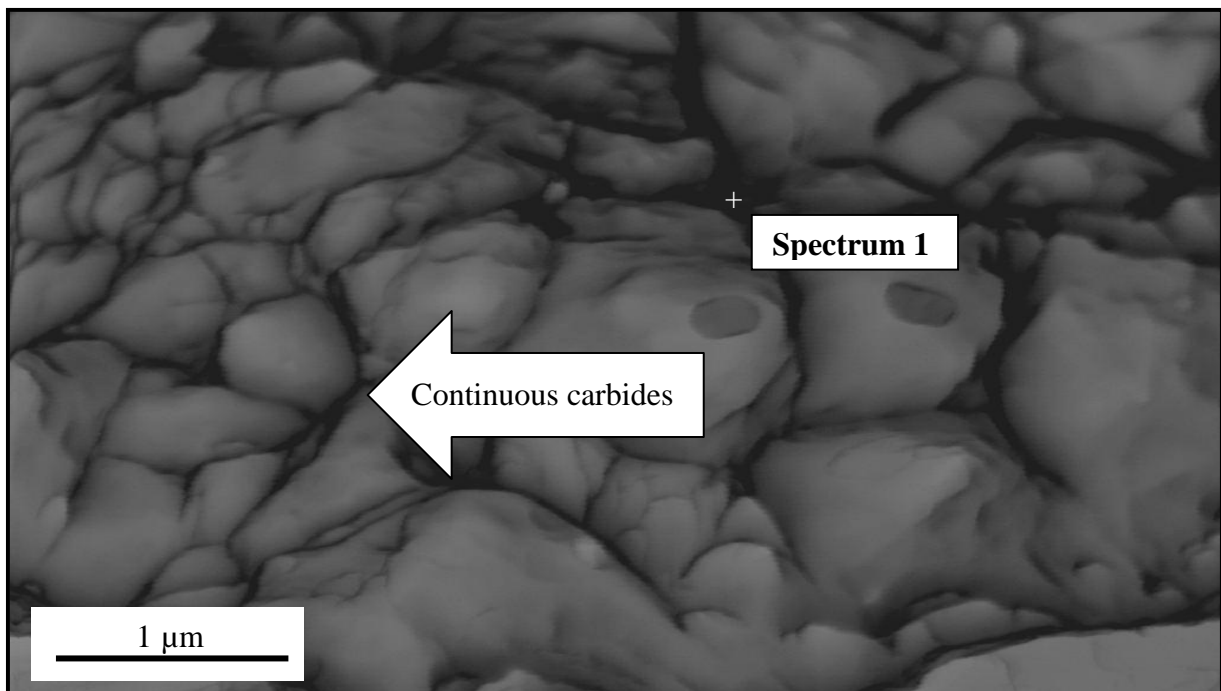


Figure 4.20 SEM Fractographic for Alloy 2 at Room Temperature before heat treatment (as cast)

Table 4.8 XRD Analysis for Alloy 2 before heat treatment

Element	C	Cr	Mn	Fe	Ni
Weight%	6.84	1.69	0.67	88.37	2.43
Atomic%	25.44	1.45	0.54	70.71	1.85

Figure 4.21 represent the fracture surface of a specimen of alloy 2 which was tested at -50°C .

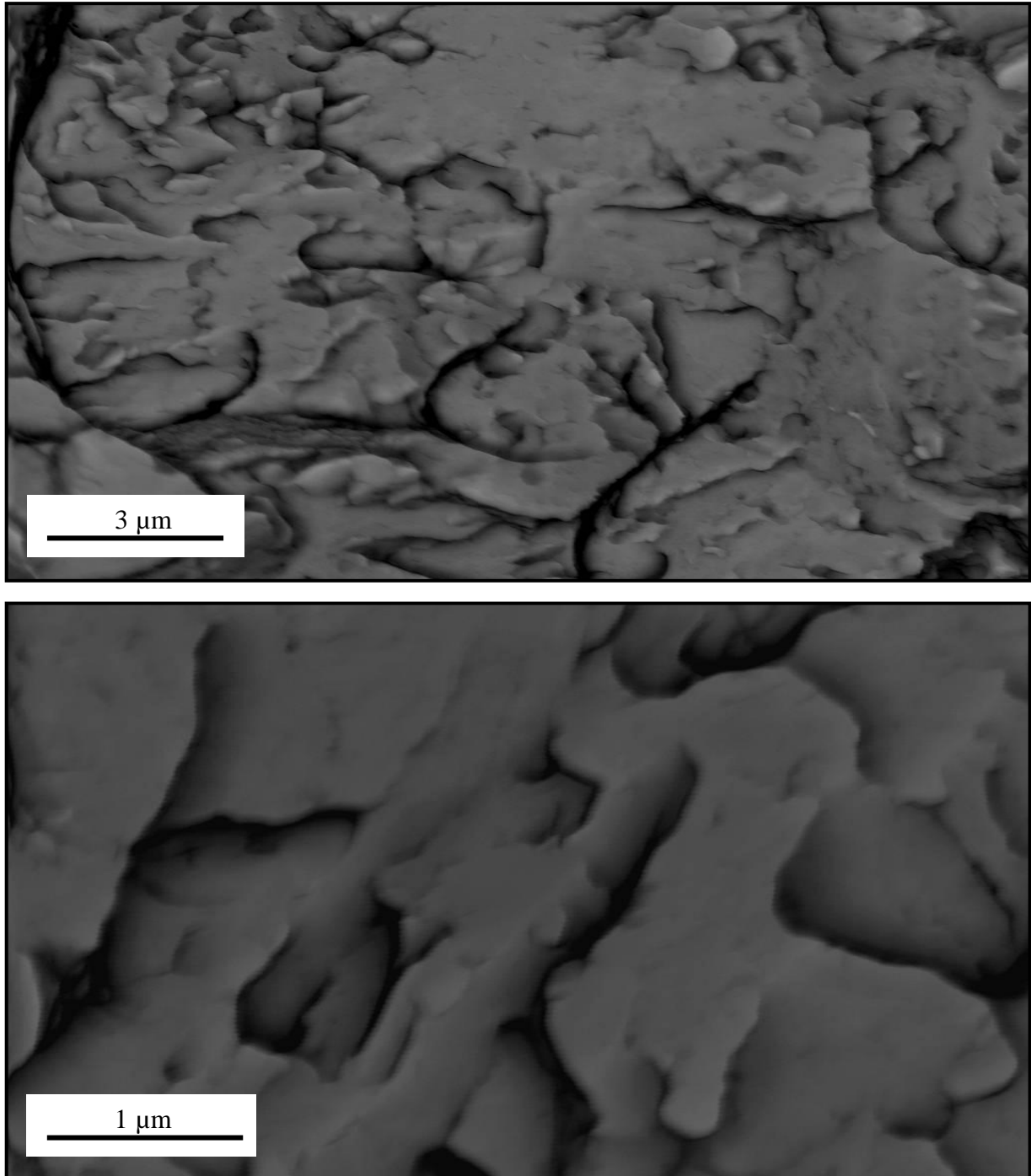


Figure 4.21 SEM Fractographic for Alloy 2 tested at -50°C before heat treatment (as cast)

Low test temperature changed the ductile dimples mode at room temperature into complete facets indicating cleavage fracture.

4.2.4.2. SEM Fractographic Investigation after heat treatment for alloy 2

Figure 4.22 illustrates the fracture surface after the heat treatment cycle (quenching-tempering)

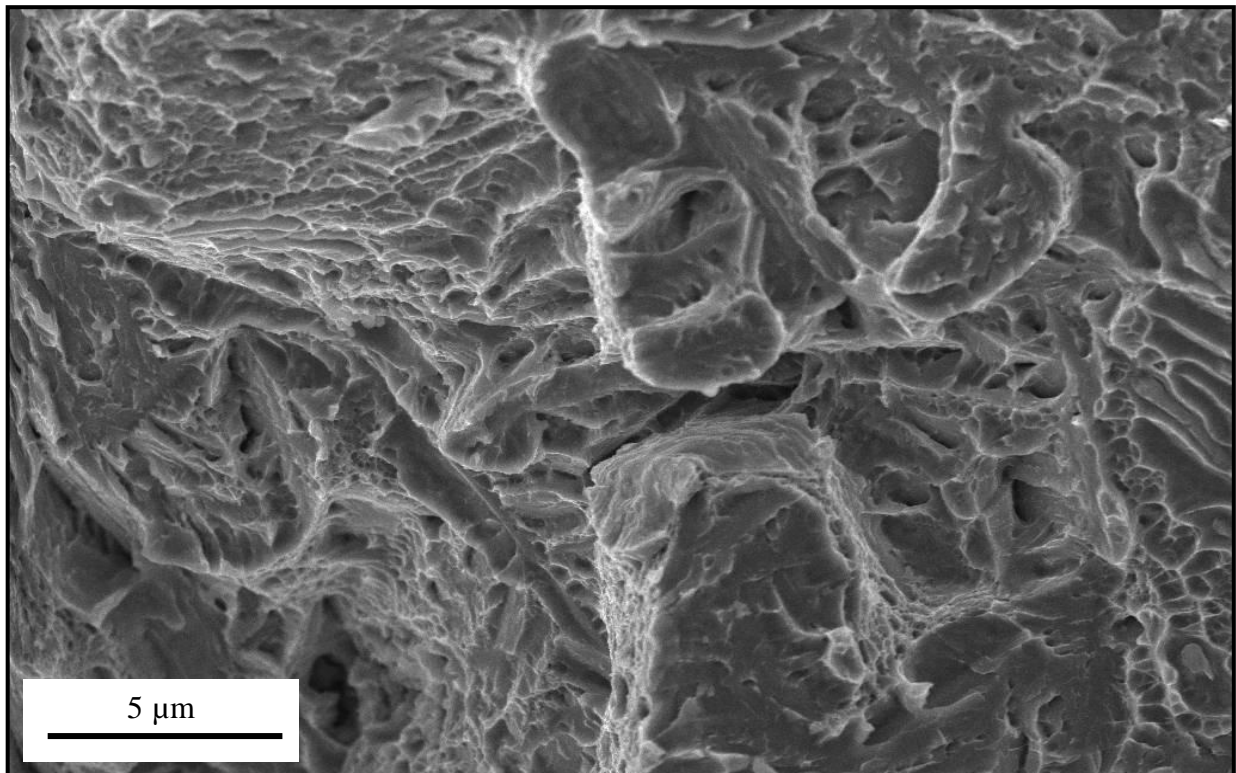


Figure 4.22 SEM Fractographic for Alloy 2 at Room Temperature after heat treatment

It is clear that the fracture surface shows complete facets with some impeded carbides, so as to the heat treatment has not any beneficial effect on the mechanical properties. These facets refer to the low values of impact toughness at room temperature after the heat treatment cycle.

A qualitative XRD analysis was applied to the impinged carbides as illustrated in [figure 4.23](#) and tabulated in [table 4.9](#)

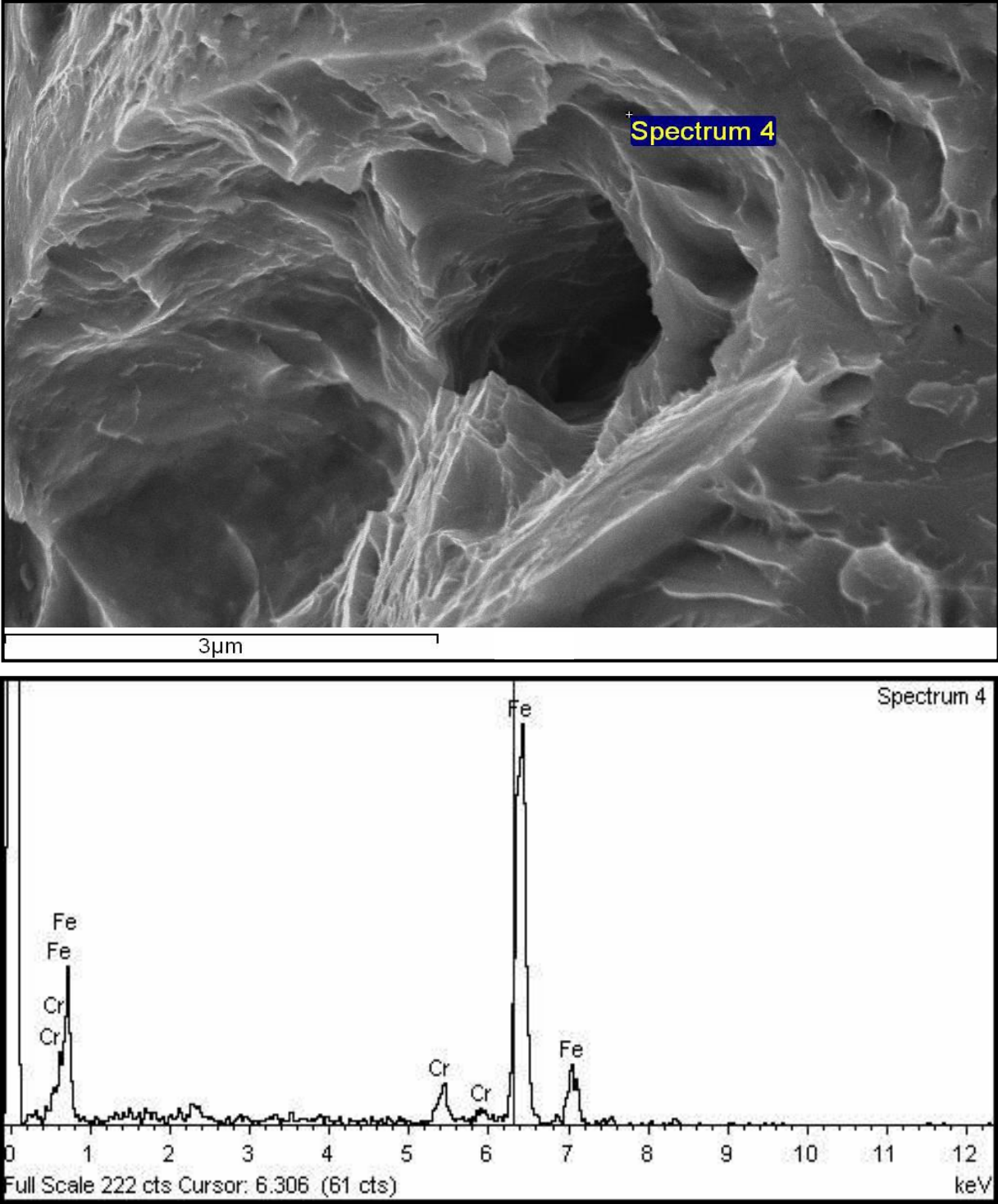


Figure 4.23 XRD for Alloy 2 after heat treatment

Table 4.9 XRD Analysis for Alloy 2 before heat treatment

Element	Cr	Fe
Weight%	4.75	95.25
Atomic%	5.09	94.91

The common carbides found by the XRD analysis are Chromium carbide and iron carbide.

Figure 4.24 gives illustration for the heat treatment fracture surface at -50°C .

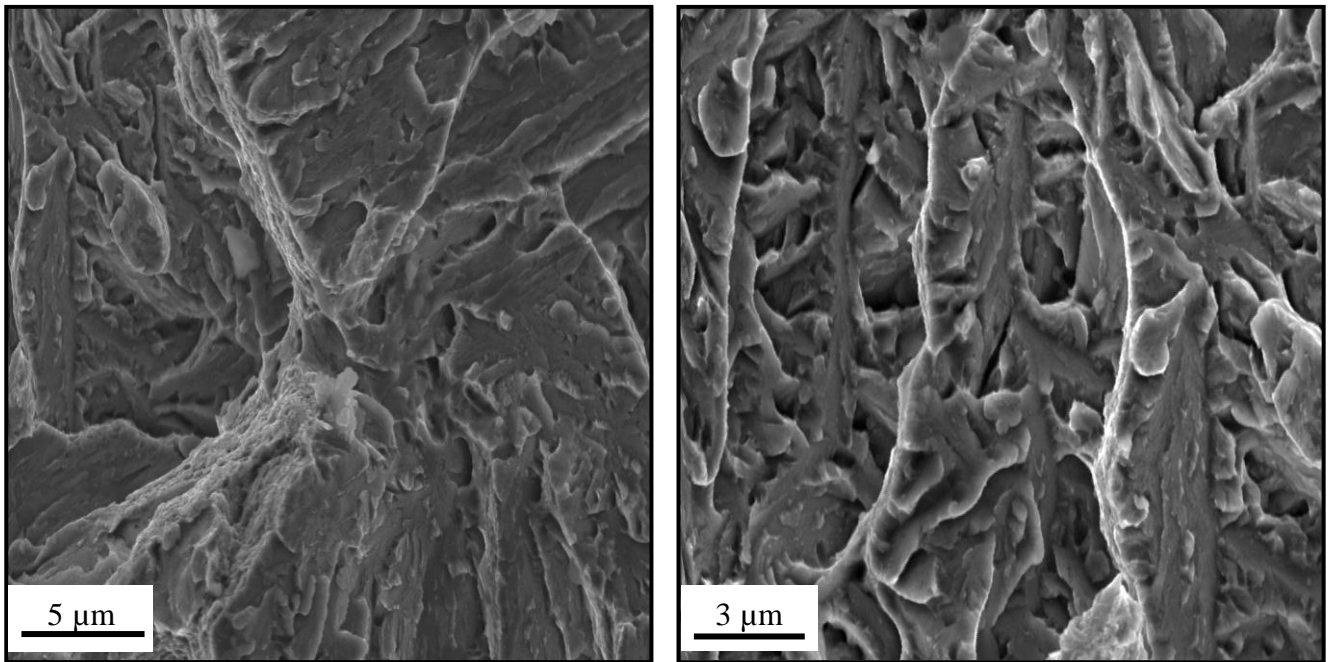


Figure 4.24 SEM Fractographic for Alloy 2 at -50°C after heat treatment

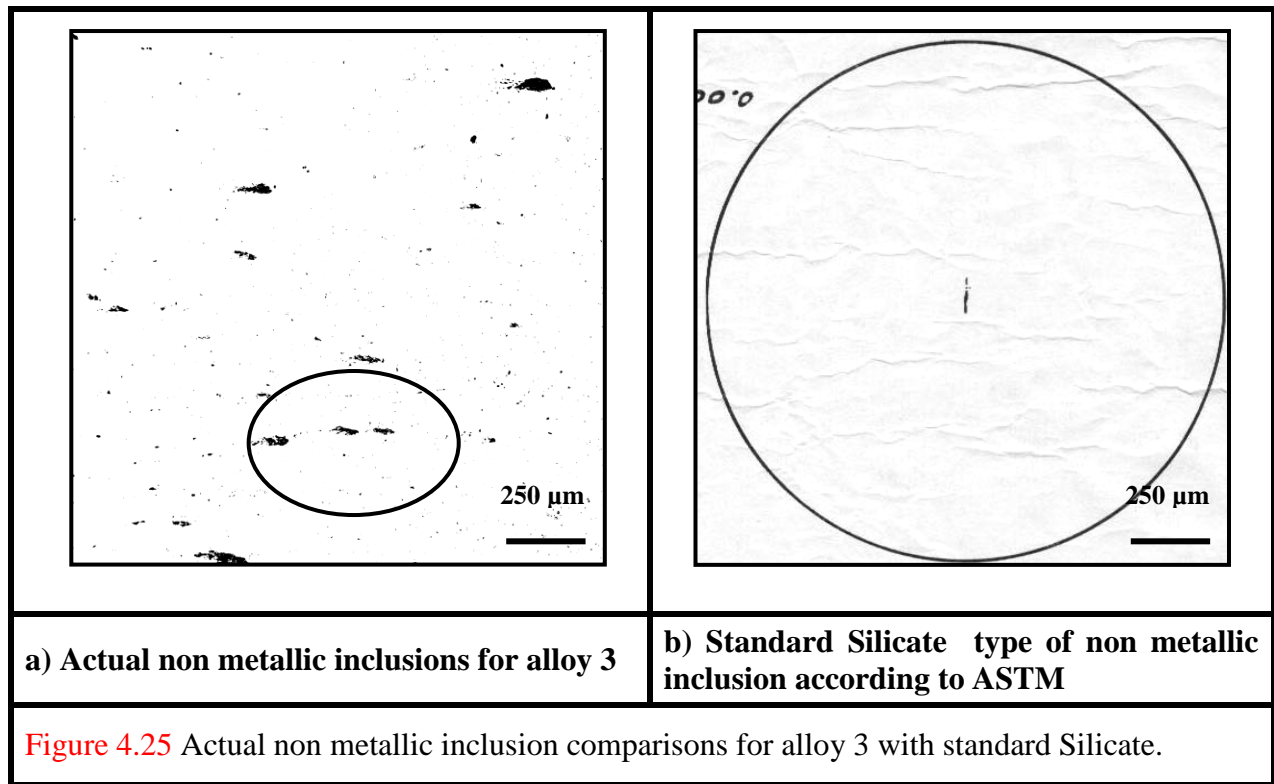
Figure 4.24 illustrates that the fracture surface is consists of small facets which leads to easy fracture (low toughness) at low temperature.

4.3. Investigation of alloy 3

Niobium is working as a grain refiner even at low concentration in alloy. Alloy 3 was designed to contain 0.06 % Niobium in order to increase the strength and toughness.

4.3.1. Non metallic inclusions in alloy 3.

Figure 4.25 represents the non metallic inclusions of investigated alloy 3.



Alloy 3 contains non metallic inclusion mixture of silicates and oxides as illustrated in figure 4.25. It is noticed that the amount of non metallic inclusions is higher than that found in the previous alloys, as it was the last portion of the 100 Kg melt.

4.3.2. Microstructure investigation for alloy 3.

Figure 4.26 represents both the as cast and heat treated microstructure of alloy 3.

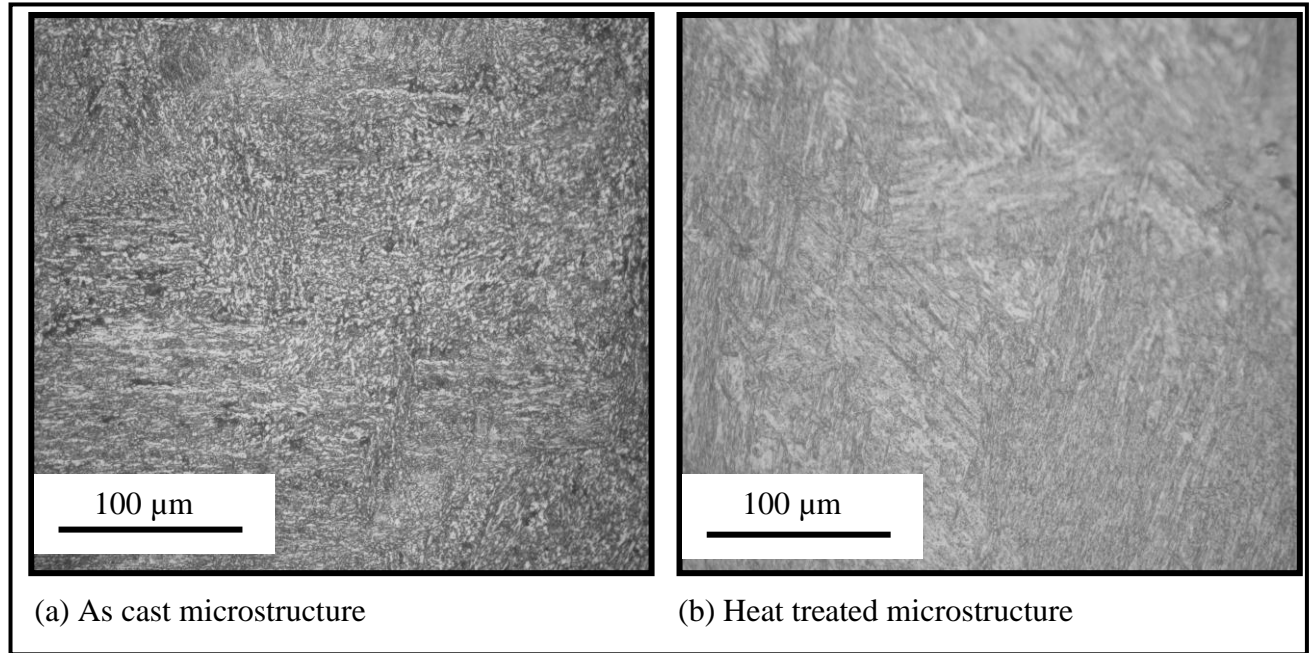


Figure 4.26 Microstructure for alloy 3

The refining effect of Niobium is reflected on the as cast microstructure where it is composed of fine martensite structure. The heat treatment is severely coarse the martensite structure which would negatively affect the mechanical properties [11-24-25-26].

4.3.3. Mechanical properties evaluation for alloy 3

4.3.3.1. Tensile test results for alloy 3

Tensile test was used as a tool to evaluate the effect of heat treatment. Table 4.10 illustrates the tensile results for alloy 3.

Table 4.10 Actual tensile test properties for alloy 3

Alloy	Condition	Specimen number	Tensile mechanical properties	
			UTS [MPa]	Mean UTS [MPa]
Alloy 3	As cast	1	938.85	930.9
		2	922.37	
		3	931.48	
	Heat treated	1	848.67	862.6
		2	882.6	
		3	856.53	

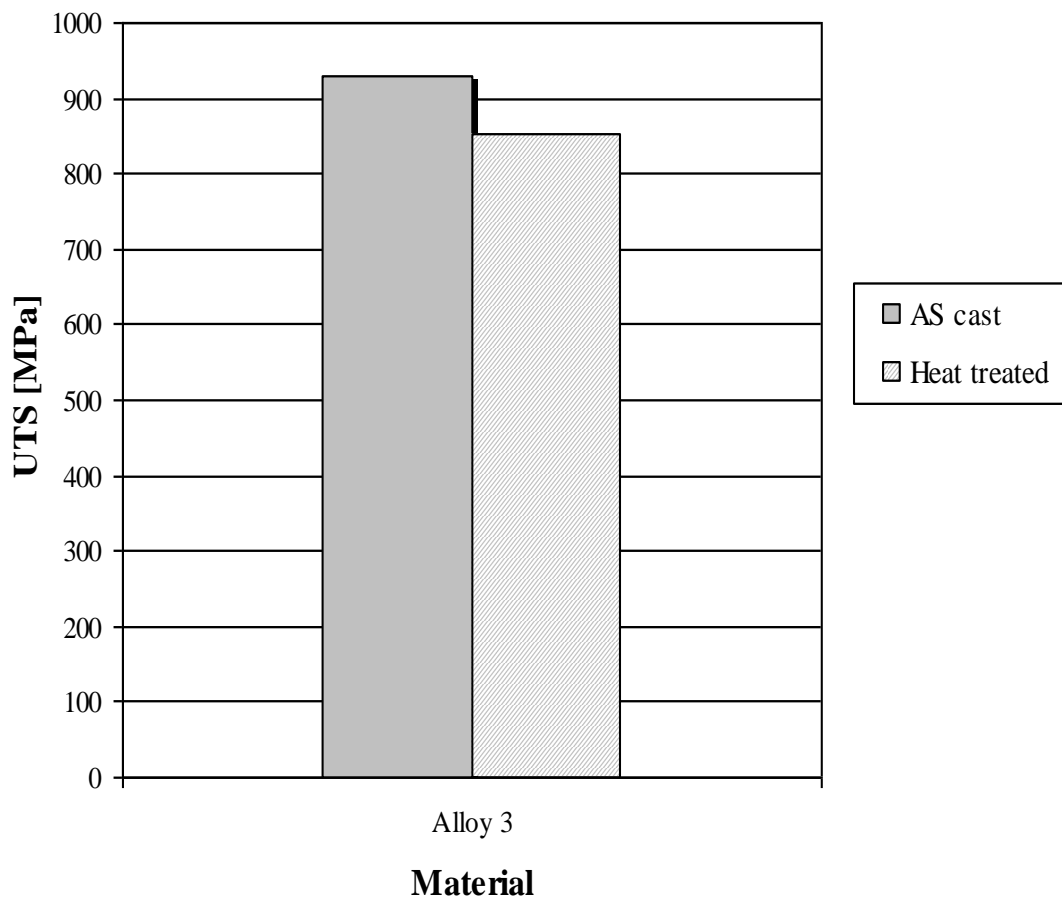


Figure 4.27 Tensile test results for alloy 3

The ultimate tensile strength of the as cast state is higher than the heat treated which was expected from the microstructure previously investigated, consequently, the applied heat treatment was not suitable for alloys containing Niobium micro-alloying.

4.3.3.2. Impact test results for alloy 3

Impact toughness at different ambient temperatures has been measured for both states (as cast-heat treated) and tabulated in [table 4.11](#) and represents in [figure 4.28](#).

Table 4.11 Impact properties for alloy 3

Condition	Test temperature [°C]	Mean energy value [J]
As Cast	Room temp. (27 °C)	11.3
	-20	9.7
	-40	8.1
	-60	6.6
	-73	5.4
Heat Treated	Room temp. (27 °C)	9.2
	-20	8.3
	-40	6.5
	-60	5.7
	-73	5.2

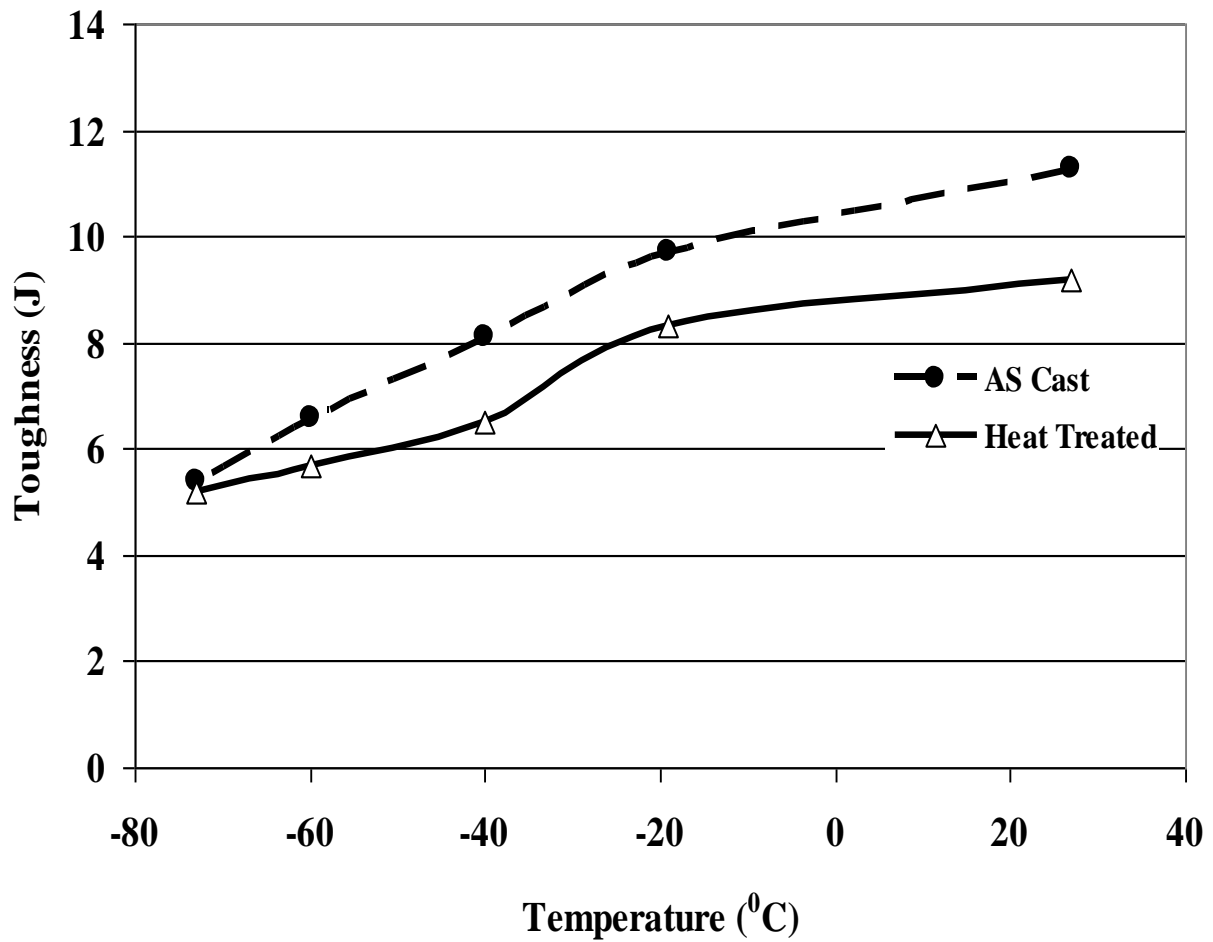


Figure 4.28 Impact toughness results for alloy 3 before and after heat treatment

It is noticed that the steel alloy 3 loss some toughness as it is subjected to deeply low temperature. Many previous works confirms what have been obtained [9-13]. On the other hand, toughness behavior of the heat treated alloy 3 is lower than that of the as cast as a result of unsuitable heat treatment.

CHAPTER 5

CONCLUSION

Chapter 5

Conclusion

1. Melting technology was successfully used to process LC2 steel alloy for cast valves, and fittings intended for low temperature applications.
2. Molten LC2 steel alloy can be modified into LC2-1 by addition of Cr and Mo.
3. Grain refinement was obtained by Nb-microalloying.
4. Quenching-tempering treatment is essentially to alter the non-homogenous martensite-ferrite cast structure into homogeneous tempered martensite structure.
5. Down to -73 °C, the impact transition temperature (ITT) was not detected.
6. Molybdenum and Chromium alloying creates a very fine martensitic structure in the modified alloy LC2-1.
7. Unsuitable quenching-tempering of alloy LC2-1 accelerates the ductile-brittle transition temperature (ITT) to -30 °C.

CHAPTER 6

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Chapter 6

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بسم الله الرحمن الرحيم

ملخص الرسالة

يمثل الصلب جزءاً كبيراً من التطبيقات الصناعية في مختلف المجالات نظراً لمتانتة وقدرته على تحمل الأحمال الميكانيكية، ومن الجدير بالذكر أن الصلب تتغير خواصه عند درجات الحرارة المختلفة، حيث تنخفض الجثالة تدريجياً مع انخفاض درجة الحرارة بينما ترتفع المتانة بمعدلات طفيفة، وتتصدر عملية إسالة الغازات النصيب الأكبر في هذا الصدد حيث يتم إسالة الغازات الصناعية من أجل سهولة نقلها عبر الحاويات أو من خلال خطوط النقل وذلك نظراً لأن النسبة بين حجم الغاز المسال والغاز في صورته الغازية كبيرة جداً قد تصل إلى 1 سائل: 60 غاز ، لذلك كانت هذه الدراسة من أجل رفع الجثالة في المسبوكات مثل المحابس والوصلات المستخدمة عند هذه الظروف، لذا فقد تم اختيار سبيكتين من الـ ASTM A352 و هما LC2 و LC2-1 ليستخدما في هذه الدراسة، حيث تم صهر مائة كيلو جرام من السبيكة الأولى في فرن حث كهربائي وتم صب عدد إثنتين من قوالب الاختبار (واى بلوك) وعقب ذلك تم إضافة عناصر سبائكية أخرى إلى باقى الصلب المنصهر بالفرن للحصول على السبيكة الأخرى، وعقب ذلك تم صب قالب واحد من قوالب الاختبار.

ومن أجل تحسين الخواص كان لابد من عمل تدقيق لحبيبات الصلب وذلك بإضافة عنصر النيوبيوم بنسب منخفضة.

لذلك فقد تم إضافة نسبة 0.06% من النيوبيوم إلى باقى الصلب المنصهر بالفرن وتم صب قالب اختبار.

تم تشغيل القوالب جميعاً لأستخراج عينات الصلادة و الشد و الصدم، وتلى ذلك عملية المعالجة الحرارية المتمثلة في التصليد (الطش) والمراجعة لنصف العينات لدراسة مدى تأثير عملية المعالجة على الخواص الميكانيكية قبل و بعد المعالجة، ومن ثم تم اختبار عينات الصلادة وعينات الشد قبل و بعد المعالجة في درجة حرارة الغرفة كما تم اختبار عينات الصدم قبل وبعد المعالجة أيضاً في درجات الحرارة المنخفضة.

أظهرت السبيكة الولي نتائج مرضية حيث اثبتت قدرتها على تحمل الصدم في درجات الحرارة المنخفضة كما كان للمعالجة الحرارية دوراً فعالاً في تحويل البناء المجهرى الى بناء متجانس بينما لم تحقق كلا السبيكتين -الأخريين نتائج مقبولة لأختبار الصدم في درجات الحرارة المنخفضة على الرغم من الزيادة الكبيرة التى تحققت في اختبار الشد لكلا السبيكتين وذلك نظراً لعدم جدوى المعالجة الحرارية.

صفحة الموافقة

الإسم : محمد جميل محمد عبد الغنى

العنوان :

"بعض التحقيقات على الصلب الكربونى المسبوك المستخدم فى درجات الحرارة المنخفضة"

التوقيع

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يعتمد،،،

وكيل الكلية للدراسات العليا و البحوث
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جامعة بنها
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رسالة للحصول على درجة الماجستير فى الهندسة الميكانيكية

"بعض التحقيقات على الصلب الكربونى المسبوك المستخدم فى درجات الحرارة المنخفضة"

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