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Research Article

A Comparative Study of the Effect of Thermal Treatments on the Mechanical behavior of Tool Steels

Daniel Martin Sandhi[Ȧ*], Rahul Davis[Ȧ], Ashish Masih[Ȧ], Roshni Deepika Hemrom[Ȧ], Ashish Samual[Ȧ] and Noel Vinsent Chand[Ȧ]

[Ȧ]Department of Mechanical Engineering, Shepherd School of Engineering & Technology, SHIATS, Allahabad, UP, India

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Abstract

Thermal treatments have been widely used as a medium of improving the physical and mechanical properties of tool steels. A Comparative study on conventionally heat treated and cryogenic treated S7and M1 specimens has been presented in this paper. Now a day's cryogenic treatment is regarded as one of the most important processes in the field of manufacturing, it is a contemporary method of processing metals to make them more wear resistant and durable. Cryogenic treatment is an appended process to conventional heat treatment process. The main objective of cryo-treatment is to convert retained austenite to martensite. Due to this conversion, all the properties of the metal increase. Here specimens are initially subjected to conventional heat treatment at austenitizing temperature of the metals respectively and are subjected to Shallow Cryogenic Treatment at -84^{o}C for 3 to 8 hours or Deep Cryogenic Treatment(DCT) at -196^{o}C for 24 hours. The changes in the microstructure were studied using radical metallurgical microscope. Here investigation is to compare about the microstructure, and durability of the specimens before and after cryogenic treatments.

Keywords: *Tool steel, Heat treatment, Cryogenic treatment, Retained Austenite, Martensite, Microstructure*

1. Introduction

Cryogenic processing had its US origins in the 1940s, be it all a primitive process compared to today's procedures.
Steel cutting tools were immersed into liquid nitrogen for a brief period of time, removed from the liquid, allowed to warm up, and placed into service on production lines. As a result of the thermal shock associated with the rapid rate of cooling, tools would occasionally crack or chip. Some tools also became brittle because of the newly formed, untempered martensite[G Theilera, 2002]. Of the tools that survived this crude quenching, many exhibit dramatically enhanced service life. Cryogenic treatment of ferrous metals convert retained austenite to martensite. Most heat treatments at best will leave somewhere between ten and twenty percent retained austenite in ferrous metals. Because austenite and martensite have different size crystal structures, there will be stresses built in to the crystal structure where the two co-exist. Cryogenic processing eliminates these stresses by converting the majority of the retained austenite to martensite. Austenite is a soft phase which is a solid solution of carbon and iron [K. Surekha *et al*, 2012].

This untransformed austenite is brittle and lacks dimensional stability, which allows the metal to break more easily under loads. To eliminate austenite, the quenching temperature has to be lowered up to subzero temperature. In this temperature austenite phase is transformed slowly into a highly organized grain structure called martensite. Martensite phase having body centered tetragonal crystal structure [Susheel Kalia, 2010].

Martensite is a finer and harder material that brings high wear resistant and better dimensional stability that is very desirable in carbon steels. Cryogenic treatments can produce not only transformation of retained austenite to martensite, but also can produce metallurgical changes within the Martensite [D.S. Nadig, *et al*, 2010; K. Surekha et al, 2012; Francois Cardarell, 2008; George Krauss, 2005].

The martensitic structure resists the plastic deformation mush better than the austenitic structure, because the carbon atoms in the martensitic lattice lock together the iron atoms more effectively than in the more open-centered cubic austenite lattice.

Cryogenic Processing is not a coating; it changes the structure of the material being treated to the core and in reality works in synergy with coatings [Pal Singh *et al*, 2011]. Cryogenic treatment of tool steel gives many advantages, which are described as:

- Longer wearing components - generally extends life of tools and parts by 300% or more
- Creates a denser molecular structure
- Decreases brittleness.
- Increased durability of drill bits, cutting and milling tools

*Corresponding author: **Daniel Martin Sandhi**

- Decrease wear of friction bearing components
- Reduce stress
- Reduced warping/cracking of susceptible components
- Enhanced performance
- Reduced heat
- Treated items will exhibit increased life leading to dollar savings
- Process can be applied to items that are new/used or sharp/dull and best of all sharpening or dressing of worn tools will not destroy treatment effects

2. Research Methodology

The materials considered for the study i.e. M1 and S7 were machined to a required dimension of (55x10x10) mm with a notch angle of 45^o. Seven specimens of each group of steels were taken. The chemical composition test was conducted and analyzed for each steel group which is tabulated in Table no: 1, 2.

Table 1 Chemical Composition of S7

C	Si	Mn	V	Mo
0.500	0.250	0.700	3.250	1.400

Table 2 Chemical Composition of M1

C	Si	Mn	P	S	Cr	Mo
0.78 0.88	0.20 0.50	0.15 0.40	Max 0.030	Max 0.030	3.50 4.00	8.20 9.20

2.1 Heat Treatment

M1 and S7 Tool Steels are selected [J. A. Charles, *et al*, 1997,]. The materials selected in the study were under gone through various heat treatment process listed below:

For M1 tool Steel

The machined specimens of M1 tool steel were slowly and uniformly heated to a temperature of 815^oC and were soaked for 1hour in the furnace. The next step is to harden the heated specimens i.e. the specimens were quenched in a cold water bath to bring it to room temperature followed by tempering to a temperature of 550^oC for 1 hour and allowed to cool in air.

For S7 tool Steel

The machined specimens of S7 tool steel were slowly and uniformly heated to a temperature of 820^oC and were soaked for 1hour in the furnace.

Table 3 Thermal Treatment Temperatures

Elements	S7	M1
Hardening Temp ^0C	820	815
Tempering Temp ^0C	550	550
Annealing Temp ^0C	820	815
Soaking time	60 min	60 min

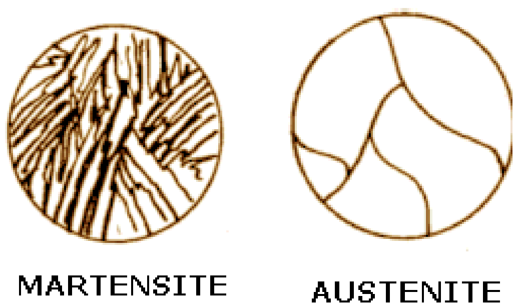
The next step is to harden the heated specimens i.e. the specimens were quenched in a cold water bath to bring it to room temperature followed by tempering temperature of 550^oC for 1 hour and allowed to cool in air.

2.2 Cryogenic Treatment

The cryogenic treatment was done in BA-03 Cryocan manufactured by Indian Oil Corporation. The Heat treated specimens of each group HCT, AC, HTCT, HTC, CT (Ref. Tab. 4) were subjected to Deep Cryogenic Treatment (DCT). For DCT, the hardened specimens were quenched in liquid nitrogen to -196^oC at room temperature for 3 hours and soaked at -196^oC for 24 hours and finally heated back to room temperature for 6 hours followed by tempering at 550^oC for 60min. The retained austenite exhibiting after the conventional heat treatment is eliminated after cryogenic treatment. The treatment alters the microstructure and mechanical properties of the material by converting the retained austenite into martensite.

This treatment is done to make sure there is no retained austenite during quenching. When steel is at the hardening temperature, there is a solid solution of Carbon and Iron, known as Austenite. The amount of martensite formed at quenching is a function of the lowest temperature encountered. At any given temperature of quenching there is a certain amount of martensite and the balance is untransformed austenite. This untransformed austenite is very brittle and can cause loss of strength or hardness, dimensional instability, or cracking. Fig. 1 shows the structure of austenite and martensite.

Quenches are usually done to room temperature. Most carbon steels and low alloy steels undergo transformation to 100 % martensite at room temperature. But, high carbon and high alloy steels have retained Austenite at room temperature. To eliminate retained Austenite, the temperature has to be lowered. Liquefied gases, such as liquid nitrogen and liquid helium, are used in many cryogenic applications. Liquid nitrogen is the most commonly used element in cryogenics and is legally purchasable around the world [J. Speera,D.K. Matlocka, B.C. De Coomanb, J.G. Schrothc, 2003].



(a) (b)

Fig. 1 Structure of Austenite and Martensite

2.3 Metallographic study

Microstructure determination was carried out by Radical Metallurgical Microscope. The finally treated specimens were first leveled by using emery paper of different grades (80, 60, and 100) so as to make the surface scratch free. A freshly prepared etchant NITAL of proportion approximately 1:10 ratio of Nitric acid and Ethyl alcohol is applied to the surface of the specimens to reveal the micro constituents of the material. The images were captured by a digital image capturing device and were processed. Finally the captured images were compared by the actual micro structural images of the tool steels to find the difference in the microstructure and mechanical behavior.

2.4 Hardness Test

The hardness of the final prepared specimens was measured by Rockwell Hardness testing machine. This 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 usually 10kgf. When equilibrium has 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. 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. The permanent increase in depth of penetration, resulting from the application and removal of the additional major load is used to calculate the Brinell hardness number, which can be calculated through the following formula:

$$= 2P/ \pi D(D-\sqrt{D-d^2})$$

P = Load Applied
D = Diameter of steel ball in mm
D = Diameter of intendation in mm

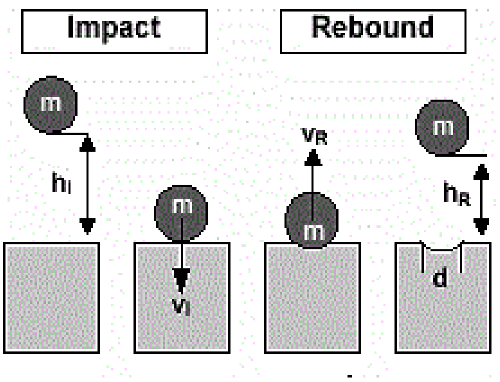


Fig. 2 Hardness Principle

2.5 Charpy Instrumented Impact test

Notched-bar impact test of metals provides information on failure mode under high velocity loading conditions leading sudden fracture where a sharp stress raiser (notch) is present. The energy absorbed at fracture is generally related to the area under the stress-strain curve which is termed as toughness in some references. Brittle materials have a small area under the stress-strain curve (due to its limited toughness) and as a result, little energy is absorbed during impact failure. As plastic deformation capability of the materials (ductility) increases, the area under the curve also increases and absorbed energy and respectively toughness increase. Similar characteristics can be seen on the fracture surfaces of broken specimens. The fracture surfaces for low energy impact failures, indicating brittle behavior, are relatively smooth and have crystalline appearance in the metals. On the contrary, those for high energy fractures have regions of shear where the fracture surface is inclined about 45° to the tensile stress, and have rougher and more highly deformed appearance, called fibrous fracture.

Although two standardized tests, the Charpy and Izod, were designed and used extensively to measure the impact energy, Charpy v-notched impact tests are more common. The load is applied as an impact blow from a weighted pendulum hammer that is released from a position at a fixed height h. The specimen is positioned at the base and with the release of pendulum, which has a knife edge, strikes and fractures the specimen at the notch.

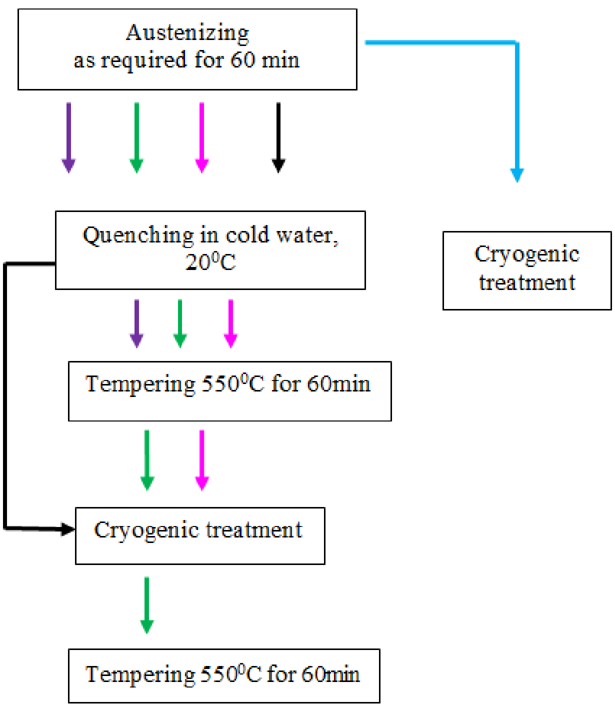


Fig. 3 Process chart of each specimen

→ **Type 1**(annealed)
→ **Type 2** (annealed → Cryogenic treated)
→ **Type 3** (Hardened → Tempered)
Type 4 (Cryogenic treated)
→ **Type 5** (Hardened → Tempered → Cryogenic treated
→ **Type 6** (Hardened → Tempered → Cryogenic treated → Tempered)
→ **Type 7** (Hardened → Cryogenic Treated → Tempered)

3. Microstructures

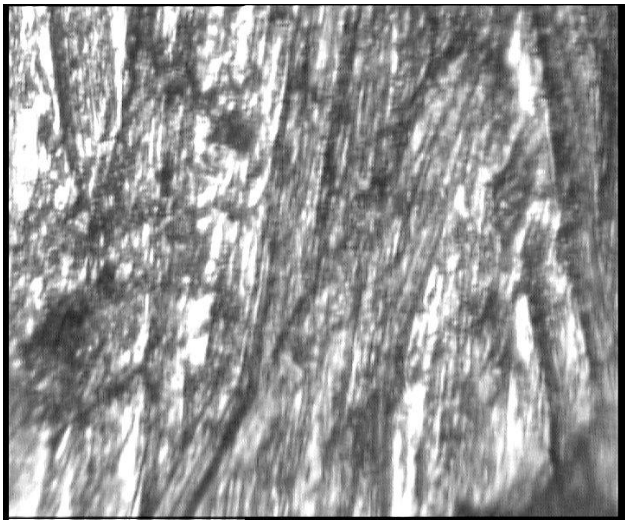


Fig. 4 Cryogenic Treated M1 metal (martensite)

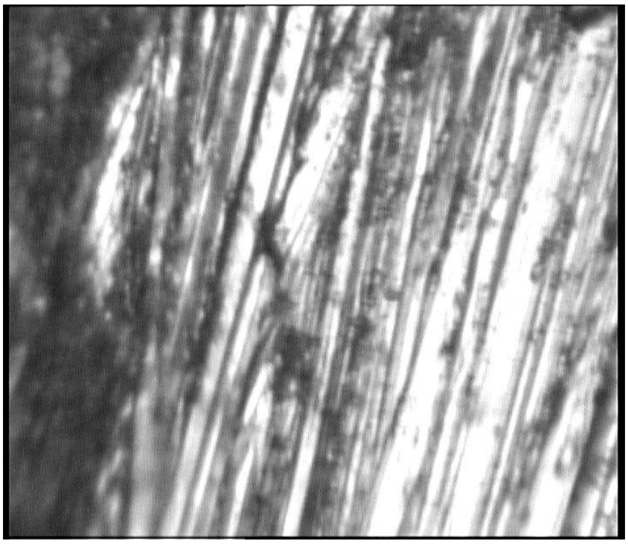


Fig. 5 Cryogenic Treated S7 metal (martensite)

4. Results and Discussion

Selected specimens of all the elements are cryogenically treated and investigations are carried out. On the basis of before and after cryogenic treatment, it is seen that retained austenite is transformed to martensite in heat treated tool steels creating a more uniform grain structure and homogeneous steel. As the voids and weaknesses are removed, tougher and more durable material is resulted. In many cases of tool steels, the transformation of austenite to martensite takes place when the part comes to room temperature. Cryogenic treatment causes additional transformation of soft-austenite to hard martensite. But it also possible to convert all the retained austenite in the tool steel by appropriate increased temperature tempering treatments that have benefit of lowering the brittleness if martensite. Advance tempering of cryogenically treated components becomes tougher better impact resisting.

Table 4 Response data of M1 Tool Steel

Thermal Treatment	Designation	Hardness No.	Impact Value
Annealed	A	38.1864	84 J
Hardening followed by Tempering	HT	31.579	27 J
Cryogenic Treatment	CT	20.02	47 J
Annealing followed by Cryogenic Treatment	AC	27.186	62 J
Hardening followed by Tempering and Cryogenic Treatment	HTC	58.823	37 J
Hardening followed by Tempering, Cryogenic Treatment & Tempering	HTCT	39.473	22 J
Hardening followed by Cryogenic Treatment and Tempering	HCT	69.157	56 J
Raw		8.70	54 J

Cryogenic treatment of tool steels also result in the formation of minute carbide particles dispersed in the martensite structure present between larger particles, this is strengthening mechanism. The small and hard carbide particles in the martensite matrix help in resisting the foreign particles. Newly formed Martensite changes its lattice and the c/a ratio same as original martensite [refer Fig 1] The formation of carbide results in more stable, harder, wear- resistant and tougher material. This intern strengthens the material without deviating the hardness.

The brittleness of the heat treated and raw metal S7 remains approximately constant throughout all process except in the specimens which is annealed followed by cryogenic treatment, the brittleness increases sharply.

The brittle property of thermally treated and raw metal M1 is increased by 84 when the metal is only annealed at 815^{o}C.

Table 5 Response data of S7 Tool Steel

Thermal Treatment	Designation	Hardness No.	Impact Value
Annealed	A	39.473	10 J
Hardening followed by Tempering	HT	82.621	6 J
Cryogenic Treatment	CT	34.638	5.8 J
Hardening followed by Tempering and Cryogenic Treatment	HTC	42.857	6.2 J
Hardening followed by Tempering, Cryogenic Treatment & Tempering	HTCT	105.116	4.8 J
Hardening followed by Cryogenic Treatment and Tempering	HCT	116.687	8 J
Annealing followed by cryogenic treatment	AC	30	120 J
Raw		75.30	4.4 J

The specimen has the highest hardness number when they are hardened and then they undergo cryogenic treatment.

Conclusion

Cryogenic treatments increase the decomposition of martensite modifying the behavior of η carbides. In simple

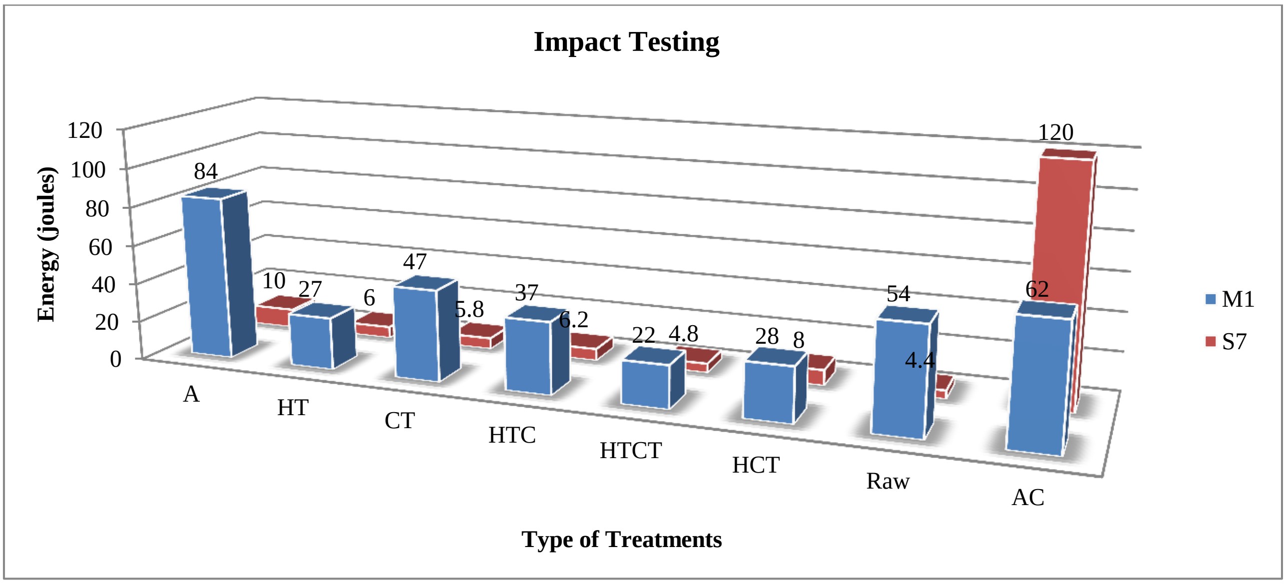


Fig. 6 Based on the values of Impact Testing

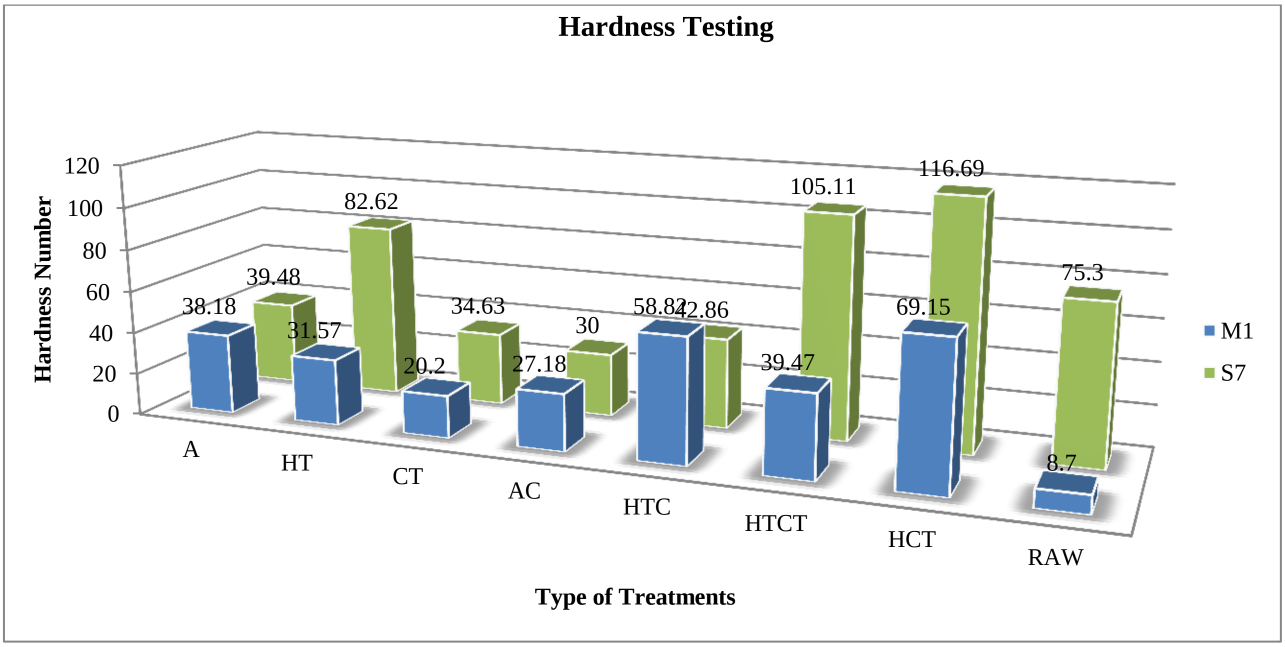


Fig. 7 Based on the values of Hardness Testing

words, cryogenic treatments polish the size of theses carbides, increment of amount and population and leading to the uniform distribution of microstructures. Hardness and toughness increase drastically by this technique.

Cryogenics materials form an integral part of the near future.

Technologies basing cryogenic treatments have broad applications in areas as metallurgy, chemistry, power industry, medicine, and rocket propulsion and space simulation.

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