Optimization of Heat Treatment parameters to facilitate machining of SAE4340 steel without compromise on Mechanical properties

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Abstract

SAE 4340 is a medium carbon low alloy steel used in many automobiles and aircraft applications because of its high strength and toughness. But its machinability is very low and hence this poses difficulty in manufacturing the parts needed for such applications. Machinability of this material can be improved by adopting suitable tool material like CBN or ceramics. But these tool materials are costly and usually need high speed machines like CNC which are suitable mainly for mass production. Moreover, these inserts are brittle and chip off fast especially when intermittent cuts are involved especially in the rough machining of castings in large numbers. For this reason, it is proposed to improve machinability by adopting suitable heat treatment to the steel without considering the type of tool material being used. This will change the basic property and micro structure of the steel to facilitate machining. The inter-critical heat treatment process is suggested wherein the material is heated between the upper and lower critical temperatures followed by water quenching and suitable tempering. To begin with, the material was normalized to 850°C in order to carry out specimen preparation. The specimens were then subjected to quenching at two different temperatures of 770 and 790°C in the inter-critical range after which tempering was carried out at 580°C. Tensile strength of around 1100 N/mm^2, impact strength of around 120J and hardness in the range of 35 to 40 HRC were obtained. Machinability tests were carried out on a centre lathe with lathe tool dynamometer set up using a brazed tip tool at low and high speeds giving a depth of cut of 1mm. The cutting forces were in the range of 60 to 70 kg force indicating good machinability. Thus without compromise in mechanical properties, good machinability was attained.

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1 Introduction

SAE 4340 is a medium carbon low alloy steel with the following composition: C: 0.38 - 0.43%; Mn: 0.6 - 0.8 %; Mo: 0.2 - 0.3%; Cr: 0.7 - 0.9%; Ni: 1.6 – 2.0% It is used widely in aircraft, particularly in critical applications such as landing gears, as a structural steel for aircrafts and aerospace equipment. It is also in automobiles (military as well as commercial) for making crank shafts, connecting rods, heavy duty axles etc. It has very good toughness and can attain very high strength in heat treated condition. However, it is found to be difficult for machining. In other words, its machinability is low.

Machinability of this material can be improved by adopting suitable tool material like CBN or ceramics. But these tool materials are costly and usually need high speed machines like CNC which are suitable mainly for mass production. Moreover, these inserts are brittle and chip off fast especially when intermittent cuts are involved especially in the rough machining of castings in large numbers.

As an alternate to this it is proposed to carry out inter-critical heat treatment before taking up for machining operation. In this process, the material is heated between the upper and lower critical temperatures followed by water quenching and suitable tempering. By this, suitable change in microstructure takes place due to the formation of dual phase steel comprising ferrite and martensite (1). A combination of these two phases gives desirable mechanical properties to the steel and at the same time there is improvement in machinability.

To begin with, the material is normalized by heating to 850°C for 2 hours and then cooling in air. Normalizing produces a fine grained structure (2) following which specimen preparation is carried out. The normalized specimens are then brought to inter-critical temperatures for partial phase transformation to austenite. This is done by heating the specimens to 770°C and 790°C for two hours in two different trials so as to obtain different amounts of ferrite and austenite in the region between lower and upper temperatures on the iron-carbon equilibrium diagram. The specimens are rapidly quenched in salt water bath at room temperature. This causes the transformation of austenite to martensite which increases tensile strength and hardness along with the decrease in ductility and impact strength. The specimens are finally tempered by heating to 580°C in two different trials for two hours and three hours. Tempering causes a drop in tensile strength and hardness with an increase in ductility and impact strength. The combination of all these developed mechanical properties gives the material the ability to be machinable.

2 Experimental details

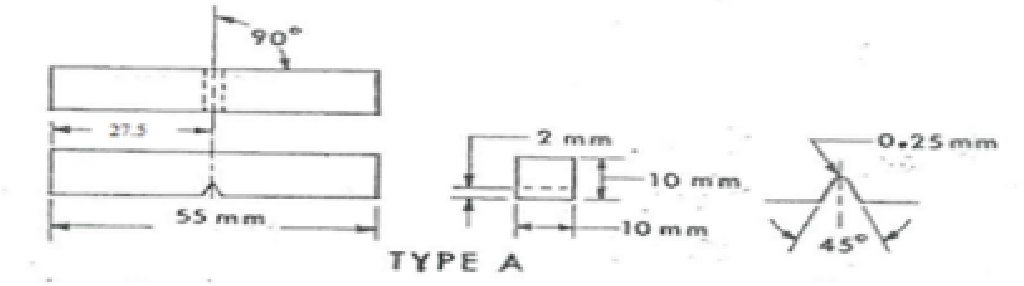
Commercially available bar stock of 20mm was selected for experimentation after ascertaining its chemical composition through spectrometry. The results are recorded as shown in Table 1.

TABLE 1

Table showing material composition of as bought SAE4340 material

Element	C	Mn	Si	Cr	Mo
Wt. %	0.438	0.710	0.253	1.23	0.216

Specimens for tensile test and impact test (Charpy method) are made as per Figures 1 and 2 respectively.



Permissible variations shall be as follows:

Notch length to edge	90±2°
Adjacent sides shall be at	90°±10 min
Cross section dimensions	±0.075 mm
Length of specimen	+0, -2.5 mm
Centering of notch	±1 mm
Angle of notch	±1°
Notch depth	±0.025 mm
Finish requirements	2µm on notched surface and opposite face ; 4µm on the other two faces

FIGURE 1

Tensile test specimen

Four sets of specimens (each consisting of 3 numbers) were normalised by heating to 850°C for two hours.Two sets were subjected to inter-critical heat treatment by austenising at 770°C and then quenching in 10% brine solution at room temperature. The other two sets were

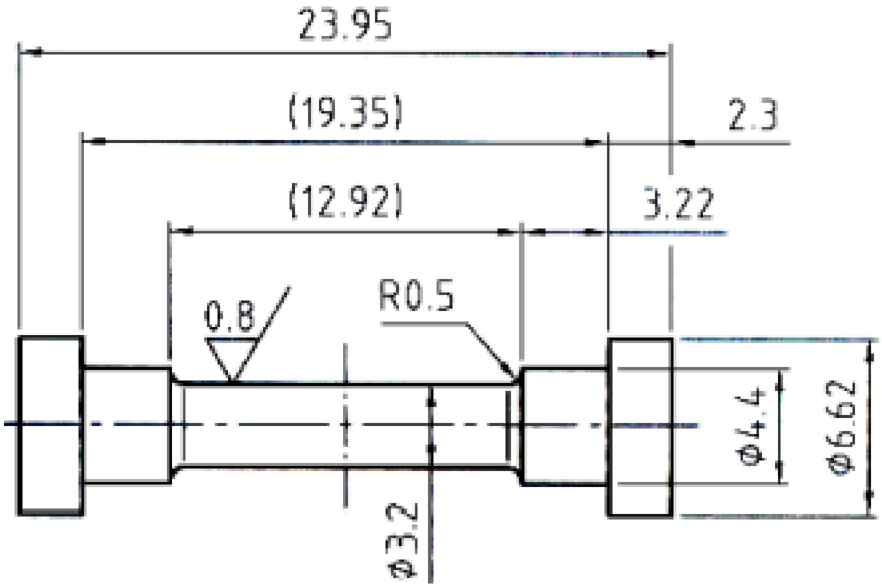


FIGURE 2

Charpy test specimen

austenised at 790°C and then quenched. The two sets of specimens quenched at 770°C were then tempered at 580°C, one set for two hours and the other for three hours. Similarly the specimens quenched at 790°C were also tempered at 580°C, one set for two hours and the other for three hours. Tensile test, hardness test and impact test were conducted for all the batches. Machinability test was also conducted by measuring cutting forces using lathe tool dynamometer on a centre lathe using ISO P30 brazed tip tool with four different combinations of speed and depth of cut. The hardness of the specimens was measured on Rockwell C scale and the values are depicted on a bar chart shown in Figure 3.

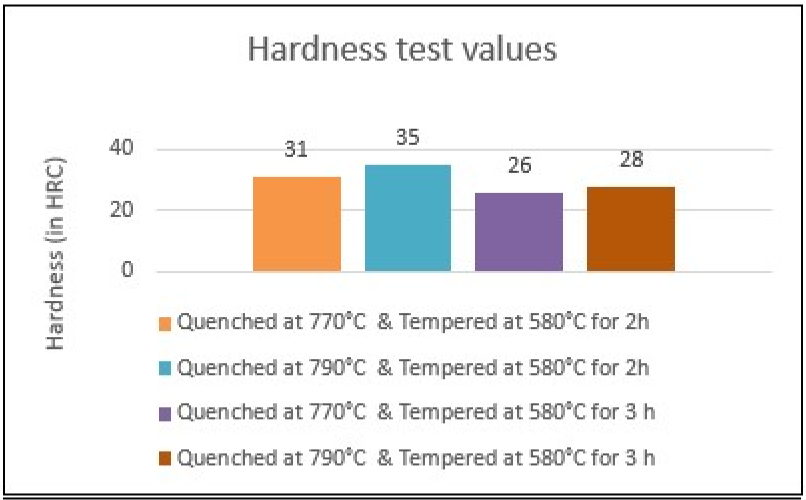


FIGURE 3

Hardness test readings

Tensile test was carried out on electronic tensometer (Kudale instruments model PC2000) and the ultimate tensile strength of the different batches is depicted on a bar chart shown in Figure 4.

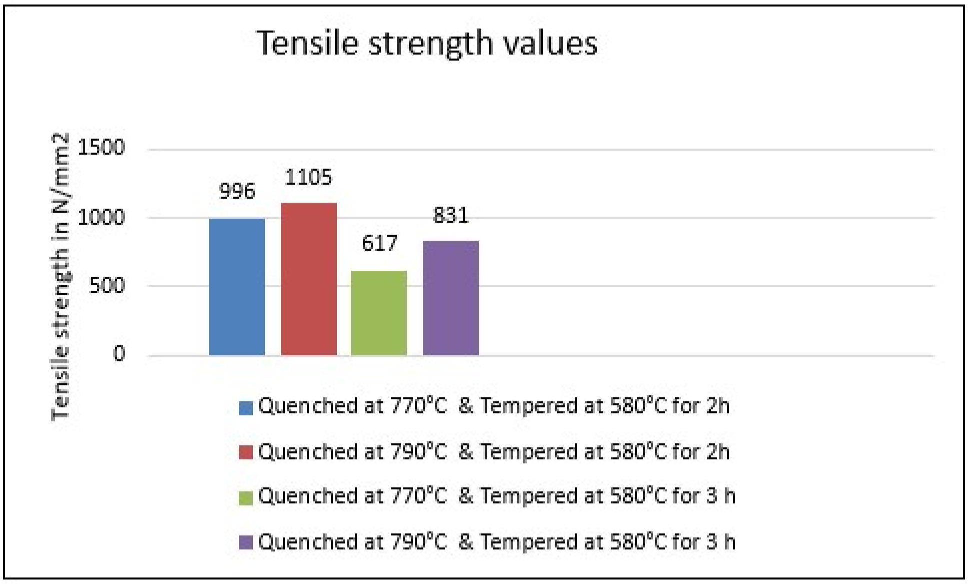


FIGURE 4

Tensile test readings

Charpy method of impact test was adopted. The impact strength of different batches is depicted on a bar

chart shown in Figure 5.

Cutting force measurement was done by turning the 20 diameter rods (also heat treated as in the case of the other specimens) on a centre lathe using a strain gauge dynamometer. Trials were conducted at 460 rpm and 750 rpm for two depths of cut of 0.5 mm and 1.0 mm.

3 Results and discussion

At 770°C, the solid solution roughly consists of 75% weight austenite and 25% weight ferrite as per lever rule. On quenching, the austenite converts to martensite, a hard and brittle structure. The material attains a hardness of around 40 HRC. Further, the increase in hardness is also due to the formation of acicular ferrite because of the presence of alloying elements like chromium, nickel and molybdenum.

At 790°C, the solid solution roughly consists of 95% weight austenite and 5% weight ferrite as per lever rule. In fact the presence of nickel promotes austenite formation. On quenching,

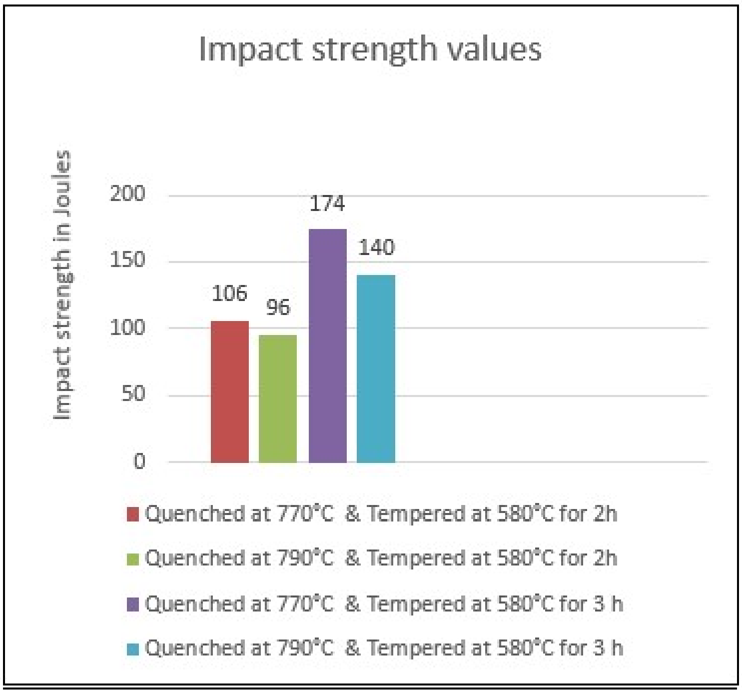


FIGURE 5

Impact test readings

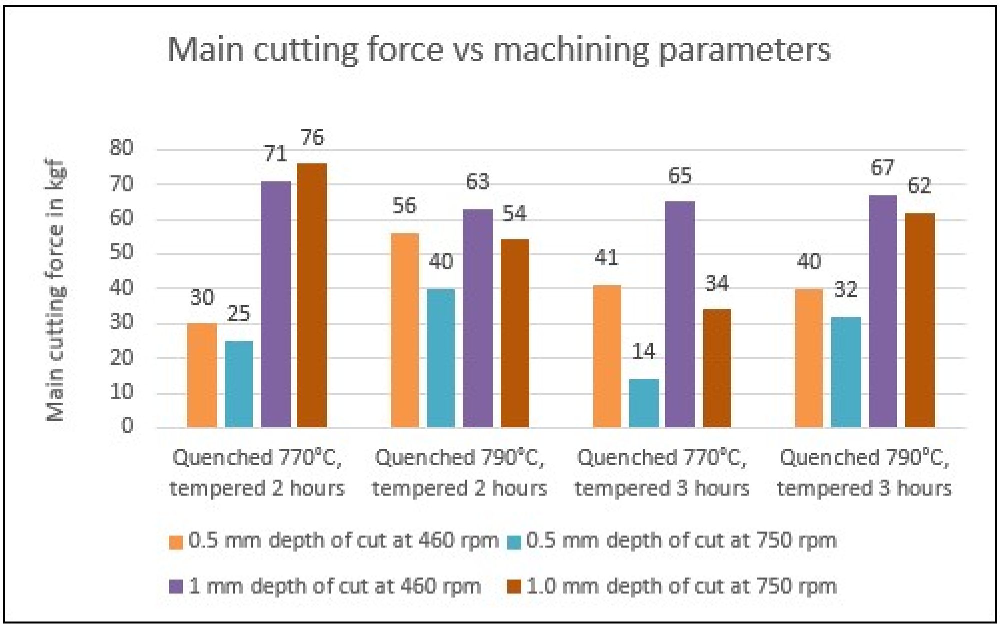


FIGURE 6

Main cutting force values

the amount of martensite formed will be much more and hence hardness value of around 50 HRC is obtained.

The material in quenched condition is very hard and brittle and not suitable for practical applications. Hence, it is subjected to high tempering by heating to 580°C for two hours and three hours. Tempering involves many basic processes such as precipitation of carbides, decomposition of retained austenite and the recovery and recrystallization of martensite structure (3). Hardness does not effectively reduce much in case of high tempering because decomposition of retained austenite is effectively retarded by manganese, chromium and silicon (4). The same applies to tensile strength which does not decrease appreciably. On the other hand, there is an increase in impact strength.

The hardness of the specimens subjected to quenching at 770°C and tempered at 580°C for 2 hours is 30 HRC which increases to 35 HRC for specimens subjected to quenching at 790°C and tempered at 580°C for 2 hours. The increase in hardness is due to more austenite content leading to the formation of more martensite. If the tempering time is increased, the amount of martensitic phase will decrease and retained austenitic phase will increase. The retained austenite phase is softer than martensitic phase so that hardness will decrease. This explains why the hardness values are 26 HRC and 28 HRC for the two specimens tempered for 3 hours. Tensile strength too followed the pattern of hardness with values of 996, 1105, 617 and 831 N/mm^2 for the respective cases. Impact strength followed just the opposite pattern with values of 106, 96, 174 and 140 Joulesfor the corresponding cases.

The ease of machining could be ascertained by measuring the cutting forces and considering the value of main cutting force in each trial. In general, cutting force values were more for 1mm depth of cut compared with the values for 0.5 mm depth of cut. These observations are on the lines made earlier (5). However, increase in cutting speed to 750 rpm gave lower values for 1 mm depth of cut as mentioned (6), indicating the ability of the brazed tip tool to operate at higher speeds.

4 Conclusion

• Austenising at 770 and 790°C produces a dual phase structure consisting of ferrite and the unstable austenite which on quenching, transforms to the hard martensite.

• Tempering the quenched steel by heating at 580°C for 2 hours brings down both hardness and tensile strength with increase in impact strength. On increasing the duration of tempering to 3 hours, the hardness values and tensile strength values show considerable drop along with rise in impact strength values.

• Taking into consideration, the practical applications of the material, the values of hardness (30HRC), tensile strength (1000 N/mm^2) and impact strength (100J) obtained by tempering the steel to 2 hours seem to be appropriate.

• The cutting forces developed at 460 rpm even for a depth of cut of 1 mm, when using a brazed carbide tool are well within 70 kgf. Further, increase in speed to 750 rpm reduces the cutting forces to 60 kgf (max.).

• Austenising at 790°C and quenching in 10% brine solution at room temperature followed by tempering at 580°C for 2 hours gives a machinable structure along with all desirable mechanical properties.

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