A REVIEW ON JOMINY TEST AND DETERMINATION OF EFFECT OF ALLOYING ELEMENTS ON HARDENABILITY OF STEEL USING JOMINY END QUENCH TEST

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ABSTRACT

Hardenability of steel is defined as the susceptibility of the steel to hardening when quenched, and is related to the depth and distribution of hardness across a cross section. There are various factors which effect hardenability of steels such as austenite grain size, carbon content and alloying elements percentage. Hardenability property is so important that a simple test is essential to measure it. There are various methods to measure hardenability of steel such as Grossman critical diameter method, Jominy end quench test, estimation of hardenability from chemical composition and Fracture test .The Jominy end-quench test, though inelegant from a scientific standpoint, fills this need. In this paper we discussed about the significance of hardenability and role of Jominy test in measurement of hardenability.

KEYWORDS

Jominy end quench test, hardenability, martensite

1. INTRODUCTION

For heat treatment, hardenability is a very useful and important property of steel. It determines the rate at which the given steel should be quenched. This also tells about the maximum hardness that can be achieved on the surface of steel of larger cross section bars, subjected to drastic quenching. A steel of high hardenability will show a uniform, high hardness along the whole length of the bar. This is because the cooling rate, even at the far end of the bar, is greater than the CCR; and the whole bar transforms to martensite. A steel of medium hardenability gives quite different results. Steels with high hardenability are needed for large high strength components, such as large extruder screws for injection moulding of polymers, pistons for rock breakers, mine shaft supports, aircraft undercarriages. High hardenability allows slower quenches to be used (e.g. oil quench), which reduces the distortion and residual stress from thermal gradients. Steels with low hardenability may be used for smaller components, such as chisels and shears, or for surface hardened components such as gears. High hardness occurs where high volume fractions of martensite develop. Lower hardness indicates transformation to bainite or ferrite/pearlite microstructures.

The hardenability of steel can be defined in several ways [1-4]. It is the ability of steel to acquire hardness being austenized and quenched. This definition emphasizes hardness. The source of hardening is the formation and presence martensite structure. Thus high hardness is related to martensite formation [5]. To get the best properties we must quench the steel past the nose of the C curve. The cooling rate that just misses the nose is called the critical cooling rate (CCR). If we cool at the critical rate, or faster, the steel will transform to 100% martensite[6]. There are various methods to optimize the least expensive and most efficient alloy system [7-10]. Quench factor analysis is also used to find hardness using data of Jominey test[11]There is no difficulty in transforming the surface of a component to martensite – we simply quench the red-hot steel into a bath of cold water or oil. There are but if the component is at all large, the surface layers will tend to insulate the bulk of the component from the quenching fluid. The bulk will cool more slowly than the CCR and will not

harden properly. Worse, a rapid quench can create shrinkage stresses which are quite capable of cracking brittle, untempered martensite. These problems are overcome by alloying. The entire TTT curve is shifted to the right by adding a small percentage of the right alloying element to the steel – usually molybdenum (Mo), manganese (Mn), chromium (Cr) or nickel (Ni) [12]. Numerous low-alloy steels have been developed with superior hardenability – the ability to form martensite in thick sections when quenched. This is one of the reasons for adding the 2–7% of alloying elements (together with 0.2–0.6% C) to steels used for things like crankshafts, high-tensile bolts, springs, connecting rods, and spanners. Alloys with lower alloy contents give martensite when quenched into oil (a moderately rapid quench); the more heavily alloyed give martensite even when cooled in air. Having formed martensite, the component is tempered to give the desired combination of strength and toughness.
In the Jominy end-quench test, though, a bar 100 mm long and 25.4 mm in diameter is heated and held in the austenite field as shown in fig.1 When all the alloying elements have gone into solution, a jet of water is sprayed onto one end of the bar as shown in fig. 1. The surface cools very rapidly, but sections of the bar behind the quenched surface cool progressively more slowly. When the whole bar is cold, the hardness is measured along its length. A steel of high hardenability will show a uniform, high hardness along the whole length of the bar. This is because the cooling rate, even at the far end of the bar, is greater than the CCR; and the whole bar transforms to martensite. A steel of medium hardenability gives quite different results. The CCR is much higher, and is only exceeded in the first few centimetres of the bar. Once the cooling rate falls below the CCR the steel starts to transform to bainite rather than martensite, and the hardness drops off rapidly.

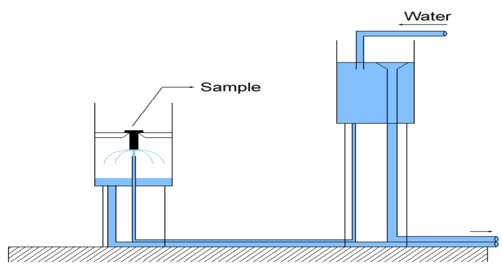

Figure 1 Layout of Jominy test rig.

Hardenability is the ability of steel to partially or completely transform from austenite to some fraction of martensite at a given depth below the surface, when cooled under a given condition. For example, a steel of a high hardenability can transform to a high fraction of martensite to depths of several millimetres under relatively slow cooling, such as an oil quench, whereas a steel of low hardenability may only form a high fraction of martensite to a depth of less than a millimetre, even under rapid cooling such as a water quench. Hardenability therefore describes the capacity of the steel to harden in depth under a given set of conditions.
Steels with high hardenability are needed for large high strength components, such as large extruder screws for injection moulding of polymers, pistons for rock breakers, mine shaft supports, aircraft undercarriages, and also for small high precision components such as die-casting moulds, drills and presses for stamping coins. High hardenability allows slower quenches to be used (e.g. oil quench), which reduces the distortion and residual stress from thermal gradients. Steels with low hardenability may be used for smaller components, such as chisels and shears, or for surface hardened components such as gears. Hardenability can be measured using the Jominy end quench test

2. EXPERIMENTAL DETERMINATION OF HARDENABILITY AND USES OF HARDENABILITY CURVES FROM JOMINY TEST

Data from the Jominy end-quench test which is performed in Jominy test apparatus as shown in fig.2 can be used to determine whether particular steel can be sufficiently hardened in different quenching media, for different section diameters. For example, the cooling rate at a distance of 10 mm (0.390 in.) from the quenched end is equivalent to the cooling rate at the center of an oil-quenched 28-mm (1.1

in.) diameter bar. Full transformation to martensite in the Jominy specimen as shown in figure 4 is heated in muffle furnace as shown in figure3.

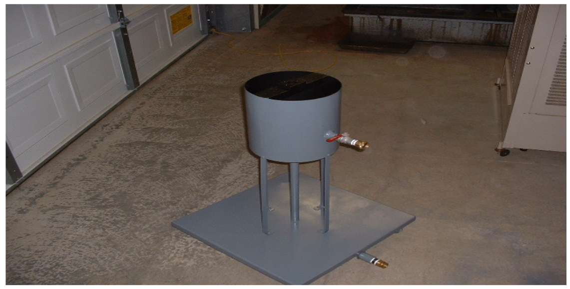

Figure 2 - Jominey End Quench Test apparatus

Figure 3 - Muffle furnace

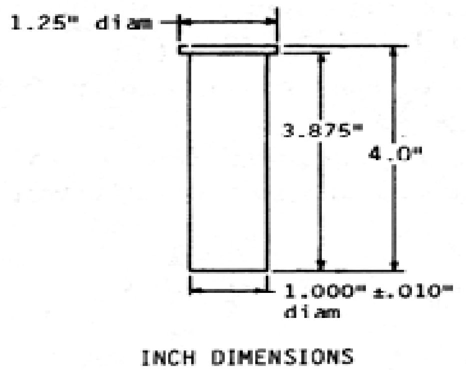

Fig. 4 Jominy test specimen

A high hardenability is required for through hardening of large components. This data can be presented using CCT diagrams (continuous cooling transformation), which are used to select steels to suit the component size and quenching media. Slower cooling rates occur at the core of larger components, compared with the faster cooling rate at the surface. In the slow cooling the surface will be transformed to martensite, but the core will have a bainitic structure with some martensite. Slow quenching speeds often are selected to reduce distortion and residual stress in components. The Jominy end-quench test measures the effects of microstructure, such as grain size, and alloying on the hardenability of steels. The main alloying elements that affect hardenability are carbon, a group of elements including Cr, Mn, Mo, Si and Ni, and boron. Carbon controls the hardness of the martensite; increasing carbon content increases the hardness of steels up to about 0.6wt% carbon as shown in fig. 5. However, at higher carbon levels, the critical temperature for the formation of martensite is depressed to lower temperatures. The transformation from austenite to martensite may then be incomplete when the steel is quenched to room temperature, which leads to retained austenite. This composite microstructure of martensite and austenite results in a lower steel hardness, although the hardness of the martensite phase itself is still.

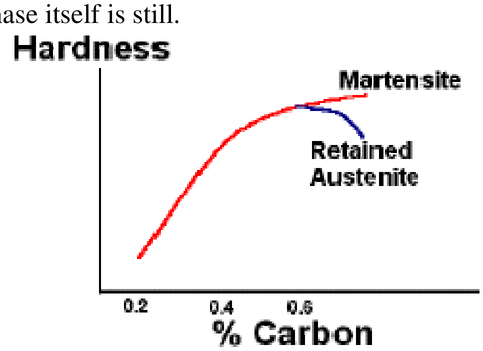

Figure5 - Graph of variation of Hardness with carbon percentage

Carbon also increases the hardenability of steels by retarding the formation of pearlite and ferrite. Slowing down this reaction encourages the formation of martensite at slower cooling rates. However, the effect is too small to be commonly used for control of hardenability. Furthermore, high-carbon steels are prone to distortion and cracking during heat treatment and can be difficult to machine in the annealed condition before heat treatment. It is more common to control hardenability using other elements and to use carbon levels of less than 0.4wt%. Other alloying elements Cr, Mo, Mn, Si, Ni and V retard the phase transformation from austenite to ferrite and pearlite. The most commonly used elements are Cr, Mo and Mn. The retardation is due to the need for redistribution of the alloying elements during the diffusional phase transfromation from austenite to ferrite and pearlite. The solubility of the elements varies between the different phases, and the interface between the new growing phases cannot move without diffusion of the slowly moving elements. There are quite complex interactions between the different elements, which also affect the temperatures of the phase transformation and the resultant microstructure. Alloy steel compositions are, therefore, sometimes described in terms of a carbon equivalent, which describes the magnitude of the effect of all of the elements on hardenability. Steels of the same carbon equivalent have similar hardenability. Boron is a very potent alloying element, typically requiring 0.002 to 0.003wt% to have an equivalent effect as 0.5wt% Mo. The effect of boron is independent of the amount of boron, provided a sufficient amount is added. The effect of boron is greatest at lower carbon contents and it typically is used with lower carbon steels. Boron has a very strong affinity for oxygen and nitrogen, with which it forms compounds. Boron can, therefore, only affect the hardenability of steels if it is in solution. This requires the addition of "gettering" elements such as aluminum and titanium to react preferentially with the oxygen and nitrogen in the steel. Increasing the austenite grain size increases the hardenability of steels. The nucleation of ferrite and pearlite occurs at heterogeneous sites such as the austenite grain boundaries. Increasing the austenite grain size therefore decreases the available nucleation sites, which retards the rate of the ferrite/pearlite phase transformation. This method of increasing the hardenability is rarely used because substantial increases in hardenability require large austenite grain size, obtained through high austenitizing temperatures. The resultant microstructure is quite coarse, with reduced toughness and ductility. However, the austenite grain size can be affected by other stages in the processing of steel, and, therefore, the hardenability of a steel also depends on the previous stages used in its production.

The influence of alloy composition on the ability of a steel alloy to transform to martensite for a particular quenching treatment is related to a parameter called hardenability. For every different steel alloy there is a specific relationship between the mechanical properties and the cooling rate. Hardenability is used to describe the ability of an alloy to be hardened by the formation of martensite as a result of a given heat treatment. One standard procedure that is widely utilized to determine hardenability is the Jominy end quench test. The heating and cooling treatment of the steel specimens have a great effect on the phase of the microstructure of the steel specimen.

The addition of alloys or coarsening of the austenitic grain structure increase the hardenability of steel. Any steel that has low critical cooling rate will harden deeper than one that has a high cooling rate of quenching. The size of the part that is being quenched has a direct effect upon the hardenability of the material.

3. DISCUSSION OF JOMINEY END QUENCH TEST FINDINGS

The jominy test was performed as per the instructions in the test rig as shown in figure6 using jominy test specimens of different steel as shown in figure 7. The specimens were heated in muffle furnace as per the instructions and quenched with water The hardness of the samples of Jominey test was measured as a function of the distance from the quenched end to demonstrate the different hardenability of the two steels with Rockwell machine. The microstructures of SAE steels-4140 and 4340 were shown in figures 11 and 12 respectively.

Fig. 6 - Jominy End Quench Test apparatus

Fig. 7 Jominy test specimen

The composition of plain carbon steel and alloy steel is shown in table 1.

Table 1- the alloy compositions of plain carbon steel and alloy steel

(wt%)	C	Mn	Cr	Ni	Si	Mo	P	S
Plain carbon Steel	0.3	0.7	0.1	0.14	0.26	0.03	0.003	0.02
Alloy steel	0.3	0.6	0.7	3.5	0.26	0.35	0.01	

The variation of hardness was measured with distance from the quenched end. The results are plotted in the graph as shown in fig.8.The alloy steel clearly has the highest hardenability, forming martensite to a greater depth than the plain carbon steel.

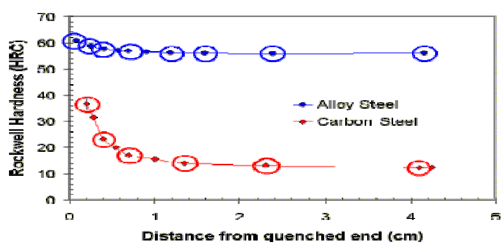

Figure 8- Hardenability curves for Jominy Test specimen between hardness and distance from quenched end for alloy steel and carbon steel

High hardness occurs where high volume fractions of martensite develop. Lower hardness indicates transformation to bainite or ferrite/pearlite microstructures. Different standard graphs plotted as shown in fig.9 and fig. 10 in jominy test for various steels. As the distance from quenched end increases the percentage of martensite decreases because of difference in the cooling rate. The fig. 10 is also showing different microstructures along jominy test bar after jominy end quench test at different points in the jominy specimen.

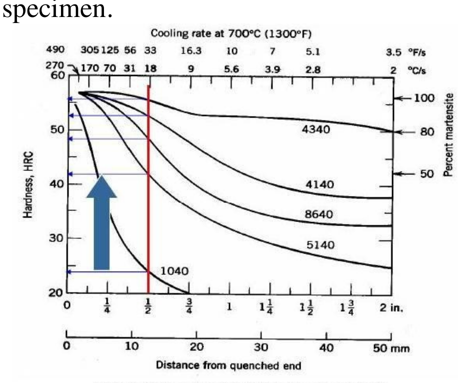

Figure 9 – Hardenability Curves for Jominy Test specimens of different materials between hardness and distance from quenched end

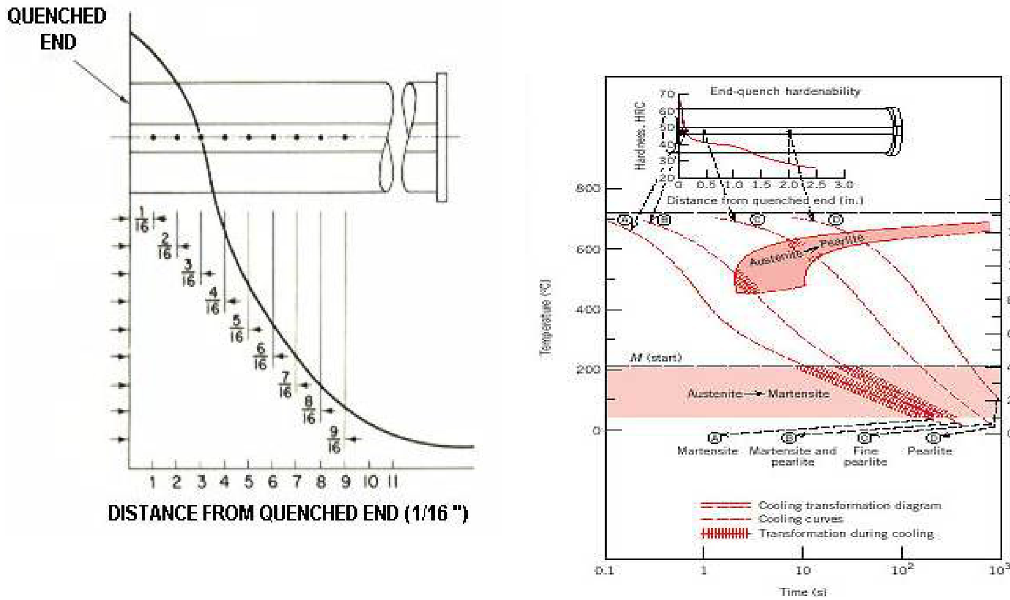

Figure 10 Different Microstructure along jominy test bar after jominy end quench test

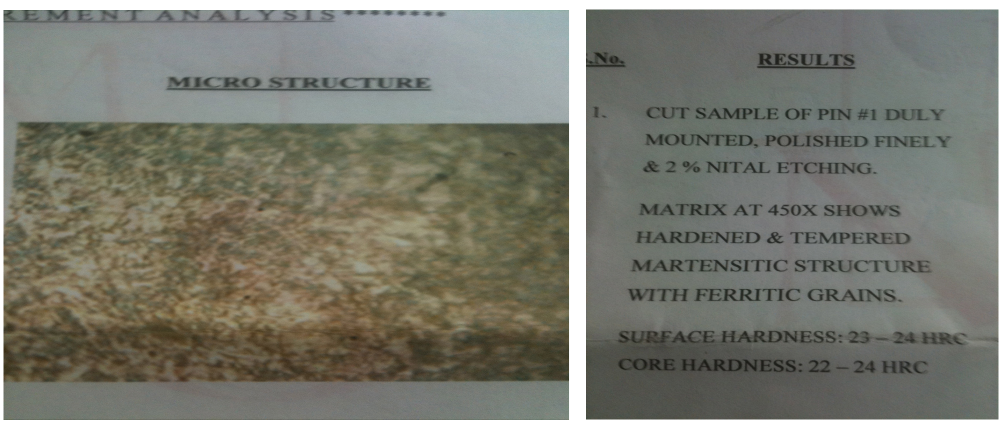

Fig.11Micro Structure Photograph for EN-19 (SAE 4140)

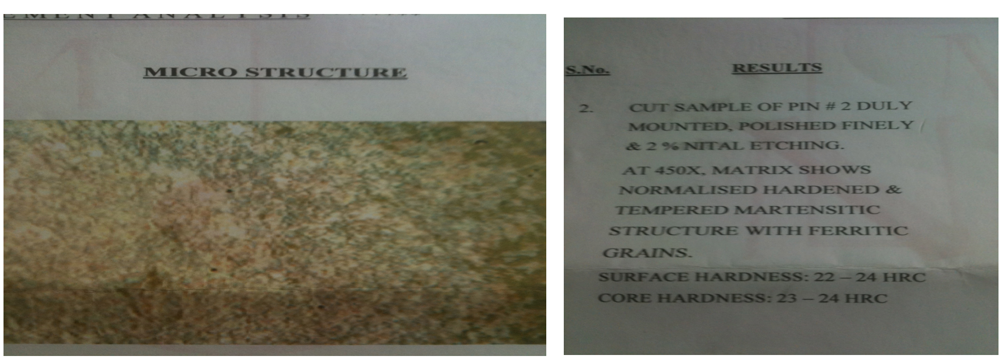

Fig. 12 Micro Structure Photograph for EN-24 (SAE 4340)

4. CONCLUSION

In this review paper we have studied the importance of Jominy test in metallurgy and change in hardenability of different steels due to change in alloying elements in steels using jominy test. We have noticed that their variations are related to micro structural change. We have used SAE 4140 and

SAE 4340 steels for making specimens and taken SEM photographs of these specimens after tests. We have studied standard graphs of Jominy test for various steels. The data from Jominy test can be used to determine whether particular steel can be sufficiently hardened in different quenching media, for different section diameters.

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REFERENCES

[1] B. Liscie, H.M. Tensi,W.Luty,Theory and technology of quenching,Springer-Verlag,Berlin,1991

[2] G.Kraus, Steels heat treatment and processing principles, ASM International, New York, 1990.

[3] E.K. Thelning, Steel and its Heat Treatment, Butterworths, London.

[4] G.E. Totten, M.A.H.Howes, Steel Heat Treatment ,Marcel Dekker, New York,1997.

[5] M.Gojic,A.Preloscan,M.Malina, Hardenability testing of low alloy chromium steels modified with molibdenium and niobium, Metallurgy 30/4(1991) pp 161-165

[6] J.V.Tuma,J.Kranje,The temperature distribution in the superheater tube, Engineering Research 66/4(2001) pp 153-156.

[7] B. Smolijan, An analysis of heat treatment process planning,Journal of Achievements in materials and manufacturing 20(2007)563-566.

[8] B. Smolijan, N. Tomasic, D.llikic,I.Felde, T. Reti, Application of Jominy test in 3D simulation of quenching, Journal of Achievements in materials and manufacturing17(2006)281-284.

[9] B. Smolijan, An analysis of combined cycle heat treatment performance process planning, Journal of materials processing technology 155/11(2004)1704-1707.

[10] A. Zehtab Yazdi, S.A. Sajjadi, S.M. Zebarjad,S.M. Moosavi Nezhad, Prediction of hardness at different points of Jominy specimen using quench factor analysis method, Journal of materials processing technology 199(2008)124-129.

[11] I. Telejko,H. Adrian, K. Skalny,M. Pakiet, R.Stasko, The investigation of hardenability of low alloy structural cast steel, Journal of Achievements in materials and manufacturing engineering 37(2009)480-485.

[12] Taher Ghrib, Fatah Bejaoui, Abdelwahheb Hamdi, Noureddine Yacoubi, Correlation between thermal properties and hardness of end –quench bars of C-48, 42CrMo4 and 35NiCrMo16 steels, Thermochimica 47(2008) 86-91.

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