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A Comprehensive Analysis of Hardenability for Different Steel Grade

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Abstract:

In the era of the engineering world, new materials are developed with controlling properties during processing, to make them an excellent candidate for a suitable application. A specific hardness for metal is often a primary requisite for many applications, so monitoring the hardness of the material is crucial during manufacturing. The hardness of the material is directly influenced by several factors such as cold working, alloy composition, and amount of martensite formation. Hardenability of steel is defined as the susceptibility of the steel to hardening when quenched and is related to the extent of depth and distribution of martensite formation across a cross-section. The controlling parameters which affect the hardenability of steels are austenite grain size, carbon content, and alloy percentage. Various methods are available to measure the hardenability of the steel. Whereas the Jominy end quench test is a widely used method to measure the hardenability of steels.

***Keywords* – Alloy addition in steel, Hardenability of steel, Jominy end quench test, Martensite formation**

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1 INTRODUCTION

Hardenability is one of the steel properties that estimate the depth and distribution of hardness, stimulated by quenching. In other words, hardenability is also defined as the composition-dependent property of steel that describes its ability to get hardened by martensite formation [1],[2].

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Hardenability is one of the most critical factors in the selection of steel for parts subjected to the heat treatment. The controlling factors of hardenability are austenitizing temperature, cooling rates after austenitizing, size of the parts, and geometry. Plain-carbon steels have low hardenability as they show relatively shallow hardening. Alloy steels show deep hardening characteristics, depending on the alloying elements and the austenitic grain size. The hardening of steel is evaluated by considering the hardening response of the steel at different cooling rates.

Steels with high hardenability are the essential characteristics for large high strength components such as large extruder screws for injection molding of polymers, piston for rock breakers, mine shaft support, aircraft undercarriages [3]. Hardenability is also the essential property for Small and high dimensional accuracy components such as die-casting molds, forging press, and stamps for coining.

The various hardenability test includes Grossman critical diameter, the Jominy end-quench test, the carburized hardenability test, and the air hardenability test. Tests that are more suited to very low hardenability steels include the hot-brine test and the surface-area-center test. The Jominy end quench test is the simplest and most reliable method of hardenability measurement. It is one of the standard methods for measuring the hardenability of steel. This method was invented by Walter E. Jominy (1893-1976) and A.L. Boegehold. [4]

The presence of the alloying element and metallurgical structure affect the hardenability. Hence the appropriate quenching rate to be selected based on the chemical composition of the steel component. The amount of cold working of the steel also affects the microstructure, and should also be considered. The hardening of steels can be understood by considering that on cooling from high temperature, the austenite microstructure of the steel can transform to either diffusion less product called martensite or a mixture of ferrite and pearlite. Ferrite/pearlite reaction involves diffusion, which takes time. However, the martensite transformation takes place instantaneously and it is a diffusionless product. The cooling rate that just lagging behind the nose of the TTT diagram is called the critical cooling rate (CCR). Martensite is obtained if the cooling rate of the steel is higher than the critical cooling rate. [5]

All alloying element except Co in steels, makes the TTT diagram shift to the right and increases the incubation period for the ferrite/pearlite reaction. This allows martensite is transformed with slower cooling rates compared with the cooling rate of the unalloyed steel.[6],[7]. The slower cooling rates also have a favorable effect to reduce internal stresses and dimensional distortion.

This article emphasizes the effects of varying carbon content on the hardenability. An attempt also made to critically discuss the influence of different alloying elements and the effect of austenitizing temperature on the steel hardenability.

2. METHODOLOGY

The test specimen we have considered is of length 100 mm and 25.4 mm diameter and cylindrical in cross-section. The specimen has a 32 mm diameter collar at one of its ends (to enable its holding in the quenching jig is used for testing [8]. The standard specimens were bought from different small scale industries of Pune with the above-mentioned dimensions. The chemical composition of the different steel grades used for the investigation is mentioned in table 1.

Sr. No	Grade and Equivalent		Elemental composition in Wt %			
	SAE/ AISI Grade	British Std. (EN)	C	S	Cr	Mo
1	1015	32B	0.10 - 0.18	0.05		
2	1040	8D	0.35 - 0.45	0.05		
3	1045	43B	0.42 - 0.48	0.05		
4	4140,1 42	19,19A	0.38- 0.45	0.15- -0.35	0.90- 1.20	0.20- 0.35
All grades of steel, Mn- 0.60 - 0.90 wt%, Si- 0.15 - 0.35 wt%, P- 0.04 wt%						

Table 1- Steel Grade details with chemical composition for Jominy End quench test

The standard specimens of exact dimensions were heated in the muffle furnace (one specimen at a time) for 45 minutes, 50°C above the austenitization temperature to transform the microstructure of steel into homogeneous austenite. After heating and soaking the specimen for 1 hour inside the furnace, it is quickly transferred to the Jominy end quench apparatus and placed in the jig within 5 sec and the specimen is quenched rapidly with liquid water. The temperature of the quenched water is maintained at room temperature. A constant flow of water is maintained from one end. In the Jominy end quench apparatus (jig), the diameter of the water orifice is 0.5” (12.5 mm). When the specimen is held in the jig, the distance between the bottom end of the specimen and orifice nozzle is maintained 0.5”. Using a valve, the water flow is so controlled that when no specimen is placed in the apparatus, the height of the water jet is 2.5”. A constant volume of water striking the end of the specimen throughout the experiment. [7]. Fig 1 illustrates the details of the Jominy end quench apparatus setup. The cooling rate is different along the length of the specimen since it is quenched from one end keeping it in a vertical position in the cooling system. The surface cools very rapidly, the cooling rate progressively goes on decreases as the distance of the specimen increase from the cooling end. Fast quenching transforms austenite into martensite as the cooling rate is higher than the critical cooling rate. It leads to the variation in martensite formation along the longitudinal section of the specimen from the quenched end. After quenching for 20 min on the fixture, the specimen is removed. Two mutually parallel flat surfaces are ground longitudinally to a depth of 0.015 in. (0.4mm). The specimens were ground flat for the removal of decarburized material from their surface using a flat-file that occurred while at the hardening temperature. Standards, such as BS 4437:1969 and ASTM A 255-67, mention the standard operating procedures for the test.[4,9] Rockwell hardness test on C scale is then performed on a ground flat surface along the length at 1/16" (about 1.6 mm) interval from the quenched end of the bar. A graph has plotted for each hardness data point vs. the distance from the quenched end.

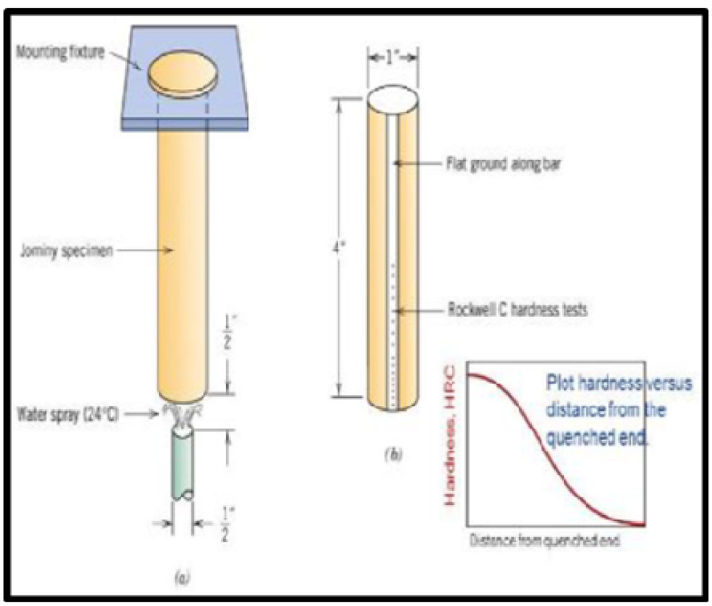

Fig. 1- Set up for the Jominy End Quench apparatus

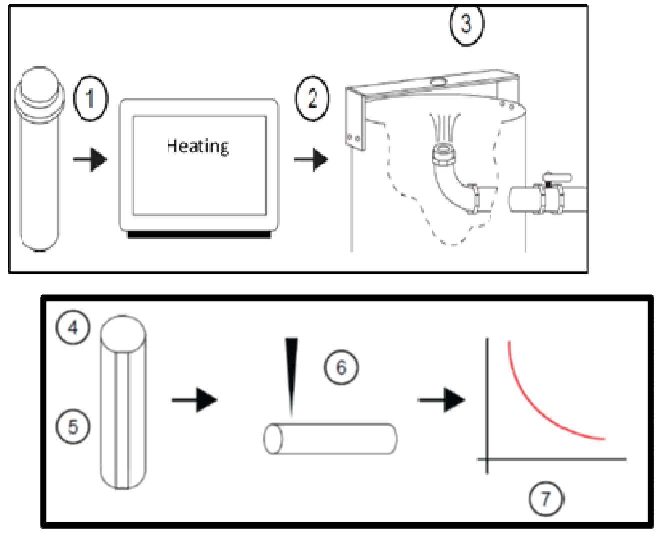

Fig. 2- Procedural Steps followed during the overall process of hardenability

3. RESULT AND DISCUSSION

Hardenability curves are constructed from the results of Jominy Tests and are tabulated below.

Jominy Sample Data - Hardness in HRC				
"J" Distance (Inch)	Steel Grades			
	SAE 1015	SAE 1040	SAE 1045	SAE 4140
2/16	14	50	54	58
4/16	11.5	39	50	56
6/16	11	30	42	53
8/16	11	26	40	50
12/16	10.8	24	32	45
1	10.7	21	27	42
1 4/16	10.4	18	23	39
1 8/16	10.4	15	23	39
1 12/16	10.1	15	21	37
2	9.6	12	20	32

Table 2- Jominy test results for various steel grade

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3.1 ***Effect of carbon content on hardenability***

Hardened steels are produced by rapidly quenching the specimen from austenitizing temperature. This involves a rapid transition from a state of 100% austenite to a large percentage of the diffusion-less product known as martensite. Martensite is defined as the supersaturated solid solution of carbon in α-Iron. This can be possible if the steel has a minimum of 0.15 % carbon. If the cooling rate is higher than the critical cooling rate, carbon effectively gets lockdown in the BCC crystal structure of the α- Iron and change the lattice structure from body-centered cubic (BCC) to body-centered tetragonal(BCT) generating a very hard and brittle phase. As the % of carbon increases in the steel, the probability of austenite to martensite transformation also increases making the steel deep hardened which is evident from Fig 3.1. The cooling rate is a function of distance from the quenched end. The cooling rate is the highest (about 30 K S^{-1}) near the end where the water jet impinges on the specimen hence % of martensite is higher at the quenched end. Hardness profile goes on gradually decreases from the quenched end, this is because the cooling rate gradually goes on decreases as the distance from the quenched end increases. [3],[10],[11].

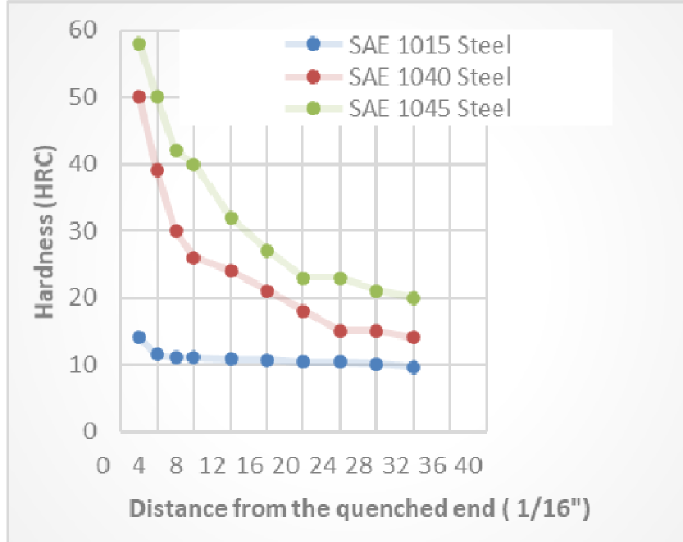

Fig. 3- A comparison plot of hardenability for three different steels with respect to the % of carbon.

For Steel grade SAE 1015, the hardness at the quenched end is also very less .this is because the carbon % is very less, hence no martensite will form and the steel will not get hardened. Martensite formation is only possible if the minimum 0.3 % carbon is maintained in the steel. Hence mild steels are not subjected to hardenability. However, as the carbon % increases in the steel, the Hardenability curve demonstrates a uniform and high hardness along the length of the bar, farther from the quenched end. This is because the cooling rate even at the far end, is greater than the critical cooling rate and the whole bar transforms to martensite. A steel of medium Hardenability gives a quite different result. Once the cooling rate falls below the critical cooling rate, carbon starts to diffuse out of the austenitic phase the steel transform to bainite or

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pearlite rather than martensite which leads to significant decreases in hardness value.

3.2 *Effect of Alloy Composition on Hardenability*

Most metallic alloying elements, except Cobalt, slow down the transformation of austenite to ferrite and pearlite which leads to an increase in hardenability. However, this can be validated with the Jominy end quench test results.

The main alloying elements that affect hardenability are carbon, Cr, Mn, Mo, Si, and Ni, and boron The addition of alloying elements increases the process cost and in some cases, it also creates a detrimental effect on the natural resources, so it is recommended to use them effectively in heat treatment. Carbon has a significant influence on hardenability, but its use at higher levels is limited, as carbon also increases the material stiffness and makes the material unsuitable for fabrication. Presence of high % of carbon increased probability of distortion and quench cracks and weld cracks.[3]

The most economical way of increasing the hardenability of plain carbon steel is to increase the manganese content, from 0.60 wt.% to 1.40 wt.%. Chromium and molybdenum are also cheaper alloying elements added to the steel to boost up the hardenability. This is confirmed with the experimental results. Fig 4 illustrates the hardenability curve for SAE 4140 steel grade moves upward for the hardenability curve of SAE 1045 steel grade.

Boron has also a significant effect when it's added to fully deoxidized low carbon steel. Alloy steel demand slower cooling rates to minimize the probability of thermal stresses and distortion.

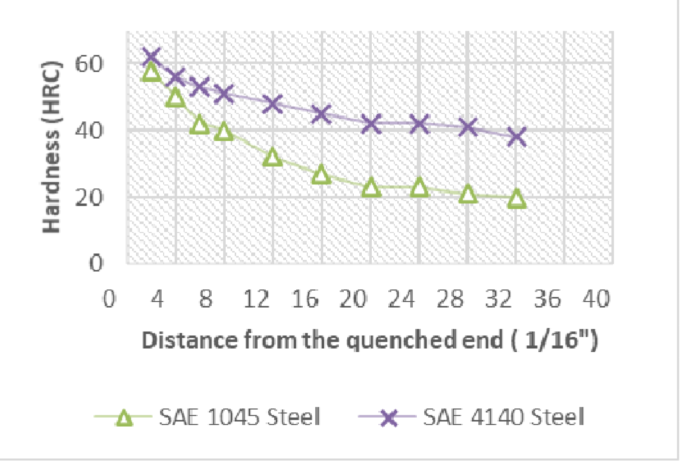

Fig. 4- A comparison plot of hardenability curve, for two different steels with respect to the % of alloy content having the same carbon concentration

3.3 *Effect of Austenitizing temperature on Hardenability*

At elevated austenite temperature, austenite grain coarsening takes place. As the austenite grain size increases, the hardenability also increases. This can be satisfied as to the austenite start to grain coarsening, grain boundary area decreases, leading to a decrease in nucleation site for ferrite and pearlite. As a result, austenite transformations to diffusion product gets hindered and transform to martensite. As the Jominy distance increases, the cooling rate of the specimen decreases, and austenite may transform into a soft phase called pearlite.

Jominy Sample Data - Hardness in HRC		
Steel Grades →	SAE 1040	SAE 1040
Austenitizing Temperature →	870°C	SAE 1040, 915°C
"J" Distance(Inch) ↓		
2 /16	50	54
4 /16	39	46
6/16	30	39
8 /16	26	32
12/16	24	30
16/16	21	25
20 /16	18	15
24/16	15	11
28 /16	15	11
32 /16	12	9

Table2- Jominy sample test results, for SAE 1040 steels with the variation of austenitizing temperature

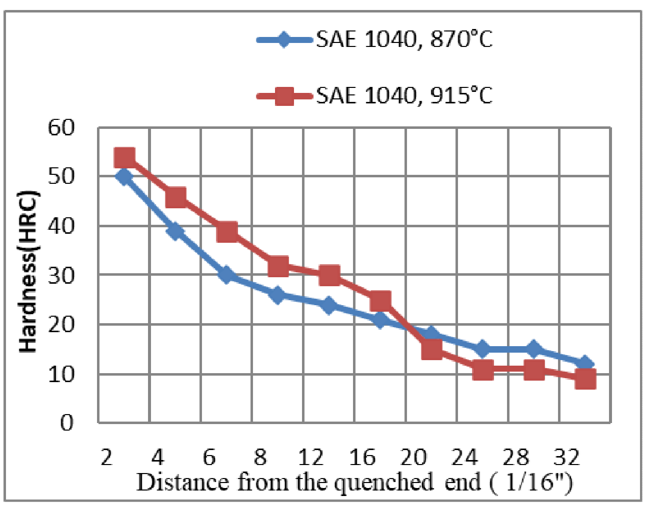

Fig. 5- A comparison plot of hardenability curve, for SAE 1040 steels with the variation of austenitizing temperature

4. CONCLUSION

Based on current research, we can conclude that

- Martensite formation is not uniform along the length of the specimen for any chemical composition of the steel. The hardness value is gradually decreasing from the quenched end as the cooling rate goes on decreases.
- Low carbon steels are less susceptible to martensite formation as a minimum of 0.3% carbon is required to form Martensite.
- For a constant cooling rate, various grades of steel have different hardness values.
- Martensite formation gradually increases for the same Jominy distance with an increase in carbon percentage.
- For the same level of carbon %, alloy steel shows additional improvement in the hardenability rather than plain carbon steel.

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