Determining case depth of low & medium carbon steels via Vicker's microhardness test

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Abstract

Many machine elements such as gears and roller bearings involve constant wear and cyclic loading. The processes of surface hardening is employed in order to improve wear resistance of steels via carburizing. This report aims to test the case depth of case hardened and heat treated steels via a Vicker's Hardness test and propose a heat treatment plan.
A diamond pyramid indentor was used to measure the Vicker's hardness value for 24 tests at 0.1mm increments with 100gf across two cross sections of processed steel. The lowest case depth was recorded in the 0.15%C heat treated steel (0.238mm) and the highest case depth was recorded in the 0.35% case hardened steel (2.01mm). These results are concurrent with the literature in relation to an increased microhardness in steels that are case hardened. At $\mathbf{1100^{\circ}}$ a proposed heat treatment plan determined that the 0.15% sample would take 3 minutes to case harden and 5 hours for the 0.35% sample. This data will be used to ensure case hardening of machine elements as they continue to be a crucial part of material fabrication, in order to improve wear resistance and plastic deformation to surface finishing.

1 Introduction

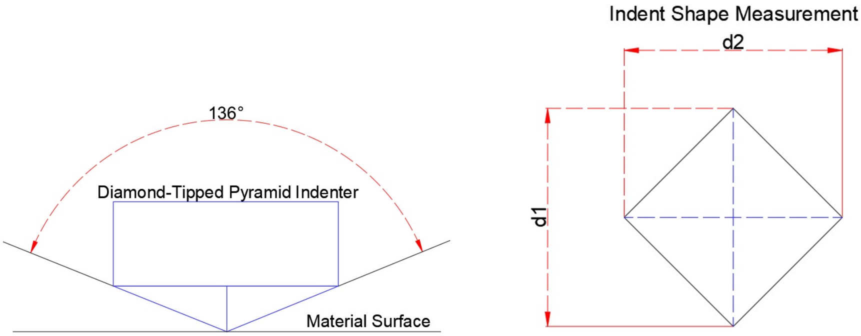
Surface hardness is the mechanical property of a materials resistance to scratching, indenting and plastic deformation. Microhardness testing of steels is completed using numerous technologies including corrosion, eletctrochemical and mechanical testing (Abdullrazzq 2016). The Brinell, Rockwell and Vicker's hardness tests are the most common mechanical hardness tests used in engineering practice. The Vicker's Hardness test is the most widely employed as it can be used on either soft or hardened steels and recorded in HV (Dossett & Totten 2013).
The process of carburizing is used to increase the surface hardness of steels, while the core of the material remains ductile. The penetration distance of carbon content that diffuses into the surface of steel is known as case depth, and this process is known as case hardening (Askeland 2011).

There are numerous applications in engineering practice which favours case hardening steels. Machine elements such as gears and roller bearings with continual contact and cyclic loading require very high surface hardening to increase durability and wear resistance, while remaining internally ductile for shock absorption (Dossett & Totten 2013). Due to the reliability required of gears and roller bearings, it is common practice for engineers to test the case hardening of samples before component manufacture (Vander 2004).
With respect to the previous foundations, it is hypothesised that case hardened steel will record significantly higher Vicker's hardness scores than heat treated samples with lower surface carbon content. These findings will be used to verify the current implementation of diffusion theory and case hardening in engineering material science.

2 Experimental Design

2.1 Methods and Materials

Two cross sectional steel samples were Vicker's microhardness tested by 3rd year mechanical engineering students at the University of the Sunshine Coast. Sample 1 was from a heat treated case ring made from 0.15wt%.C low carbon steel while sample 2 was from a case hardened 0.35wt.%C medium carbon steel block.
A Struers DuraScan - 70 with overview camera was used to apply 24 indentations at 136° in 0.1mm increments with 100 gf (0.981N) force to each Bakelite mounted sample and recorded in Table A1.
The Durascan - 70 onboard software incorporated the average of diagonal indentation to calculate a Vicker's Hardness (HV) score and recorded in Table A1. The indentation angle and diagonal surface measurements can be seen in Figure 1.



(a) *Angle of Diamond Indentation* (b) *Diagonal indent measurement*

Figure. 1: Indentation angle and diagonal measurement of steel samples

2.2 Numerical Analysis

According to Dossett & Totten (V4,2013:p1018-1021), case depth for steels under 0.28%Cwt is determined as the corresponding surface depth for a Rockwell Hardness score of 50. Interpolation in MATLAB from the hardness test conversion chart displayed in Dossett & Totten (2013), arises a Vicker's Hardness score of 513. A Rockwell hardness value of 40 is used for steels with carbon content 0.33%-0.42%Cwt (Dossett & Totten 2013). MATLAB interpolation arises a HV value of 402. These HV values are used to Interpolate and graphically identify the corresponding case depth (Figure 2).

3 Results and Discussion

3.1 Analysis of Case depth of Steel samples

After numerical and graphical analysis and reference to Dossett & Totten (V4,2013:p1018-1021), the effective case depth of heat treated 0.15%Cwt is 0.238mm and case hardened 0.35%Cwt is 2.01mm (Figure 2). Case depth was estimated graphically and interpolated with MATLAB to return a more accurate estimation. The process of carburizing has shown that steels with a case hardened layer report higher HV values (Abdullrazzq 2016) and therefore remain more resistant to surface deformation (Callister 2018).

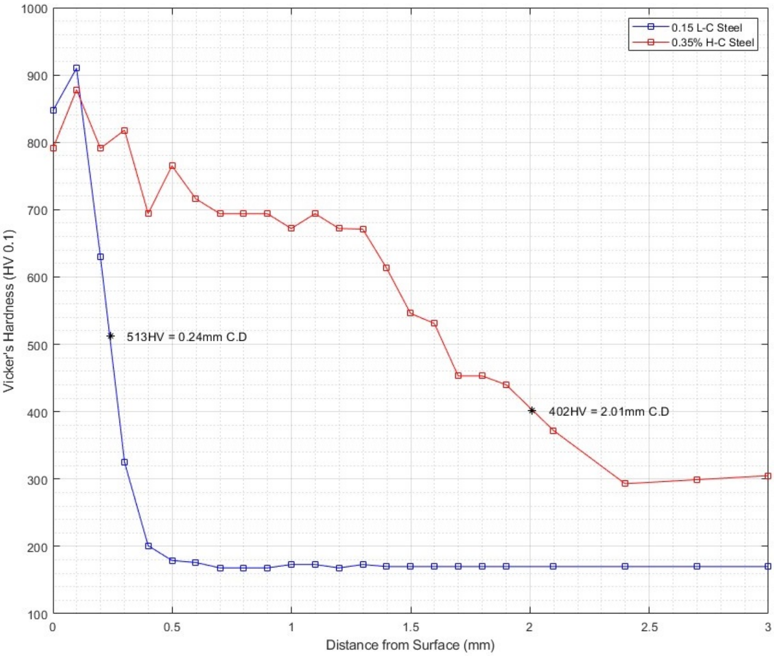
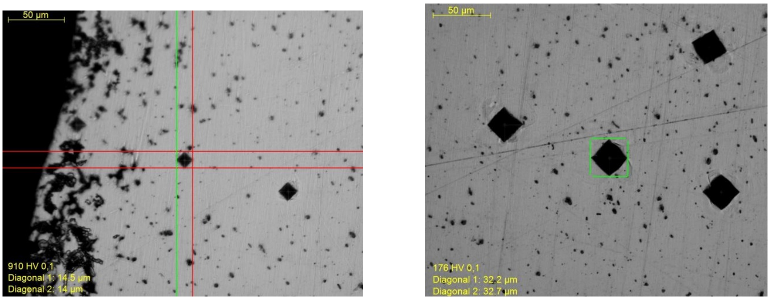


Figure. 2: Vicker's Hardness scores measured from material surface for 0.15% and 0.35% Carbon steel with interpolated case depth indication.

3.2 Analysis and Understanding of Photographic evidence

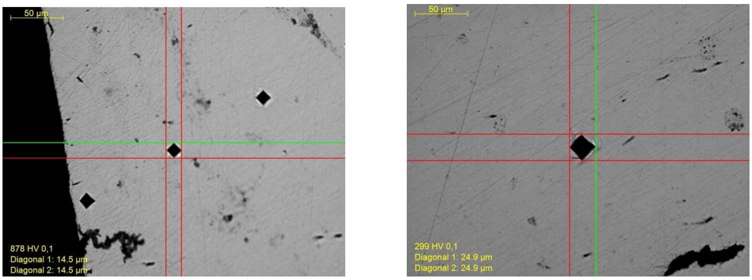
The HV score on the 0.15%C sample resulted in the instantaneous highest recorded result of 910 HV (Figure 3a). The following indentation tests recorded a reduction in hardness to 630 and 325 with 0.299mm into the surface. At the same 20x objective lens, the increase in indentation at T7 can be seen in Figure 3 b).



(a) *Diagonal 0.15%C T2 HV910* (b) *Diagonal 0.15%C T7 HV176*

Figure. 3: Indentation of 0.15%C steel at initial and final values of HV

Conversely, Figure 4 shows the indentations of 0.35% steel at Test 2 and Test 23. Even though test 2 scored a lower HV of 878 compared to test 2 of 0.15% the indentation remained minimal in comparison. After 23 tests the HV score of 299 was recorded and remained 1.7 times higher than in Figure 3b). Along with the reduction in dark deposits of the sample in Figure 3, these photographs depict the increase in diagonal measurements and reduced case depth in 0.15% sample.



(a) *0.35%C T2 HV878* (b) *0.35%C T23 HV299*

Figure. 4: Indentation of 0.35%C steel at initial and final values of HV

During the phase diagrams of $Fe + Fe_3C$, the carbon content is reduced out of the Eutectoid region $\approx 4.3wt\%C$ until it reaches the Eutectic valley $\approx 0.76wt\%C$ (Figure 5). Once the steel is under 0.76% carbon, then further treatments can be applied to reduce carbon content (Abdullrazzq 2016). As the overall carbon concentration reduces, the outer layers of the steel become easier to deface. The outer layer of the material is subjected to carbon diffusion to improve external wear resistance. In order to improve the hardness of these steels, a layer of carbon is diffused, known as carburizing (Callister 2018). Thus the process of case hardening is employed to increase surface hardness to a specific case depth (Abdullrazzq 2016).

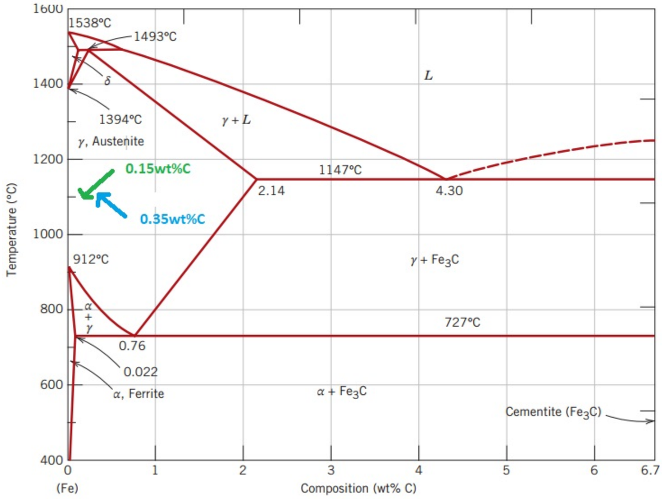


Figure. 5: $Fe + Fe_3C$ Phase Diagram with Austenite 1100° case hardening temperature indicated (Section 3.3)(Callister 2018)

With the known carbon concentrations and using industry standards and low and medium carbon steels, it is possible to design a heat treatment plan for these samples.

3.3 Heat treatment plan for determined case depths

After determination of case depth for each sample (Figure 2), it is possible to propose a heat treatment plan for interstitial carbon diffusion.

3.3.1 Heat Treatment Plan for 0.15% Low Carbon Steel

Based on appropriate carbon percentages for low carbon steel and interpolation of erf(z) scores, the following heat treatment plan could be followed to obtain 0.15% carbon case hardening at a case depth of 0.24 mm at both 1100° & 900° (Callister 2018). (Equation 1).

$$\frac{C_{x,t} - C_o}{C_s - C_o} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

Equation 1: Solution to Fick's second order partial differential equation (EQ.1)

$$T = 1100^\circ \; C_0 = 0.15\%, \; C_x = 0.45\%, \; C_s = 1.2\%, \; D = 5.3 \cdot 10^{-11}$$

$$0.7143 = 0.755\left(\frac{16.486}{\sqrt{t}}\right)$$

$$Time \approx \; 3 \, minutes \, @ \, 1100^\circ$$

$$T = 900^\circ \; C_0 = 0.15\%, C_x = 0.45\%, C_s = 1.2\%, \; D = 5.9 \cdot 10^{-12}$$

$$0.7143 = 0.755\left(\frac{49.403}{\sqrt{t}}\right)$$

$$Time \approx \; 45 \, minutes \, @ \, 900^\circ$$

It can be seen that for 0.15% low carbon steel, that there is a 15x increase in diffusion time by performing the process at 900° when compared to 1100°. Figure 6 indicates the carbon diffusion rate with respect to temperature (Dossett & Totten 2013). The change in diffusion rate due to temperature is evident due to the nature of the curve (Figure 6).

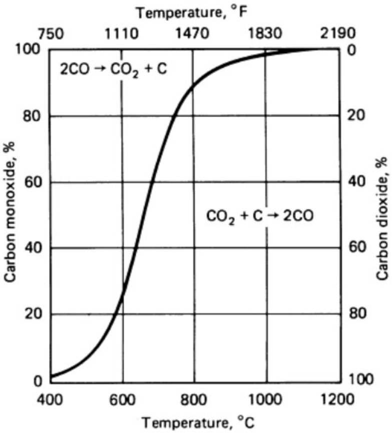


Figure. 7: Carbon diffusivity into steel occurs highest over 1000° (Dossett & Totten 2013)

3.3.2 Heat Treatment Plan for 0.35% Medium Carbon Steel

Based on appropriate carbon percentages for low carbon steel and interpolation of erf(z) scores, the following heat treatment plan could be followed to obtain 0.35% carbon case hardening at a case depth of 2.01 mm at both 1100° & 900° (Callister 2018). (Equation 1).

$$T = 1100^\circ \; C_0 = 0.35\%, C_x = 0.90\%, C_s = 1.6\%, \; D = 5.3 \cdot 10^{-11}$$

$$0.56 = 0.5461\left(\frac{138.05}{\sqrt{t}}\right)$$

$$Time \approx \; 5\, hours\, @\, 1100^\circ$$

$$T = 900^\circ \; C_0 = 0.35\%, C_x = 0.90\%, C_s = 1.6\%, \; D = 5.9 \cdot 10^{-12}$$

$$0.56 = 0.5461\left(\frac{138.05}{\sqrt{t}}\right)$$

$$Time \approx \; 45\, hours\, 12\, minutes\, @\, 900^\circ$$

It can be seen that for 0.35% low carbon steel, that there is a 9x increase in diffusion time by performing the process at 900° when compared to 1100°. Figure 7 indicates the carbon case depth with respect to temperature (Dossett & Totten 2013). The increase in carburizing temperature with an increase in case depth, further verifies the results of this heat treatment plan. As 1100° was used, this would further increase carburizing times and would result in the 'blue' line intersecting the temperature gradient at 5 hours, as depicted in Figure 7.

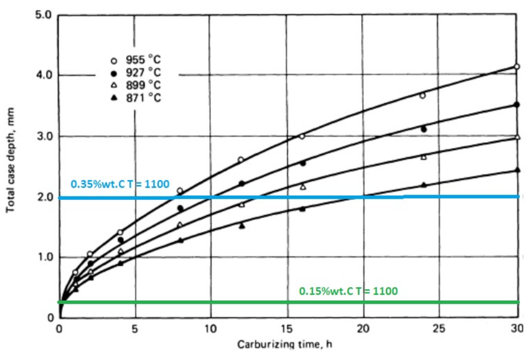


Figure. 8: Depiction of case hardening time and case depth. [Note this heat treatment plan $T = 1100^\circ$ will increase times displayed and verify the results] (Dossett & Totten 2013).

4 Conclusion

After analysis of calculations and experimental findings, it has been concluded that this experiment does verify material properties expected by 0.15% and 0.35% case hardened materials. The following conclusions were made;

1. The 0.15% sample recorded the highest hardness of HV 910 and lowest HV 176 compared to the 0.35% sample of HV 878 and HV 299.

2. However, the 0.35% sample recorded higher sustained HV values due to the thicker case depth (2mm) while the 0.15% sample had a drastic drop off after 3 tests due to the thinner case depth (0.24mm).

3. At the same carbon concentrations, for the 0.15% LC sample, it would take $\approx$ 3 minutes to case harden (0.24mm) at 1100° and 45 minutes at 900°.

4. At the same carbon concentrations, for the 0.35% MC sample, it would take $\approx$ 5 hours to case harden (2mm) at 1100° and 45 hours, 12 minutes at 900°.

5. Diffusion time is exponentially temperature dependent due to the nature of Fick's second order partial differential equations. (Equation 1).

These calculations are required in industry in order to recreate materials based off tested hardness values. These findings are used to verify the current implementation of diffusion theory and case hardening in engineering material science.

4.1 Error and Recommendations

The primary recommendation would involve the improved surface cleaning of the samples. Visible finger prints were noted during sampling and removal would have improved picture quality.
It is recommended for future studies to obtain different metals and alloys to broaden the array of tested materials. Due to the increased industry usage of stainless steels, it would be interesting to measure the surface hardness of these alloys.

References

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