Investigating the fracture behaviour of carburized and carbonitrided 16MnCr5

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Abstract. Low carbon alloys are low in cost and easily shapeable. Chemical composition of a material determines the mechanical properties. In this paper 16MnCr5, low alloy steel is surface treated via carburizing and carbonitriding in sealed quench furnace and quenched with oil. The effects of tensile deformation, strain rate behaviour and fracture characteristics were investigated by scanning electron microscope (SEM). A detailed investigation was done on case hardness how the surface treatment alters the hardness of the material from surface to core. The fracture of the specimen after surface treatment shows results with an intergranular fracture with projected burs on the fractured specimen. This paper investigates the fracture mechanism of surface treated material.

1. Introduction
Gas carburizing and carbonitriding is the widely used process for hardening the surface of the steel. The process is usually carried out in low carbon steels of 0.14-0.25%. Properties of materials changes with the change in metallurgical structure and the presence of inclusions in it. The surface treatment is mainly based on the process parameters; the atmosphere of material treated, quenching medium and materials characteristics. These factors influence the carbon diffusion rate or mass coefficient transfer. The main aim of this experimental study is to experimentally develop and understand the carburizing and carbonitriding process and study their influence in fracture mechanism. Optimizing the process parameter will provide better efficiency. Hence parameter selection plays a pivotal role in the case hardening process. A number of investigations are studied on case hardening of various steels.

Non-metallic inclusions play a pivotal in determining the fracture, corrosion and cyclic load bearing capacity. These properties determine the performance of steel, which aids in choosing for application. There are more reservations about the word inclusion, where various researchers comprise carbides and carbonitrides with other particles. [1] 13Cr-4Ni martensitic stainless steel fractograph images reveal much cuboidal shaped titanium carbonitride particle. [2] 17CrNiMo6 reheated, forged and annealed were austenitized by cyclic heat treatment in a salt bath furnace. Fractograph image shows quasi cleavage in as received 17CrNiMo6. The austenitized 17CrNiMo6 with fine microstructure with quasi cleavage and complex river patterns of small cleavages. [3] Ingot melted in a vacuum and categorized into four categories based on their treatments. The fracture stress shows that ultrafine ferrite/cementite (UF-C) has the maximum fracture stress among other parameters taken. UF-C was heat treated and warm rolled which exhibits fine grain [4].
Optimizing the parameters by saturation–value method in low-pressure carburization of 16Cr3NiWMoVNbE reveals a reduction in diffusion coefficient [5]. Using Helium as a quenching medium provides improved mechanical properties of the core of case hardened steels. No negative effects were observed in the microstructure of 16MnCr5 while quenching with helium [6]. Cryogenic treatment does not bring significant improvement to mechanical properties in 16MnCr5. Cryogenically treated 16MnCr5 shows hardness and wear resistance increased, however, toughness decreases with soaking time [7].

2. Materials and Methods

The 16MnCr5 is a Fe-alloy highly used for automotive applications because of its machinability and shape ability. However, the low-alloy steels have a low hardness value surface treatment is used to enhance the case hardness of the material. Gas Carburizing and Carbonitriding are done in the specimen. The process cycle for the gas carburizing and carbonitriding are shown in Figure 1 and Figure 2 respectively. The material is loaded in sealed quenched furnace surface treated according to the process cycle. The carbon boost potential of 0.95% and carbon + urea boost potential of 1.25 is employed in the gas carburizing and carbonitriding process. The material is quenched using mineral oil and annealing is carried out to relieve internal stress [8].

![Figure 1. Carburizing cycle.](image1)

![Figure 2. Carbonitrided cycle.](image2)
3. Properties Observation

3.1. Chemical Composition Testing

To analyze the composition of the material, the chemical composition test was carried out using OES (Optical Emission Spectroscopy). The chemical composition of the specimens is shown in Table 1.

| Composition for     | C   | Si  | Mn  | P   | S   | Cr  |
|---------------------|-----|-----|-----|-----|-----|-----|
| As received condition | 0.159 | 0.2 | 1.14 | 0.009 | 0.028 | 1.02 |
| Carburized          | 0.6 | 0.203 | 1.19 | 0.013 | 0.024 | 1.11 |
| Carbonitrided       | 0.494 | 0.216 | 0.77 | 0.023 | 0.043 | 0.0015 |

3.2. Tensile Test

Material surface treated both Carburized and Carbonitrided are tested for tensile strength and Young’s modulus. The specimen is machined as per the ASTM standard. Length of rod =300mm, Length of gauge =200mm, Diameter of gauge=12mm. Figure 4 and Figure 5 shows the load vs. displacement graph for 16MnCr5, Carburized specimen, and Carbonitrided specimen respectively. It is found that the tensile strength of 387.077 N/mm² is obtained in the Carburized sample. However, the Percentage of elongation in Carbonitrided specimen is 5% where the specimen material has about 20%. Fracture with deformation forming cup and cone structure is observed in as-received condition, where the surface treated specimen was observed with brittle fractures with projected burs.

Because of strain hardening and necking the specimen elongates up to 20% of its size cause ductile pull. The cup and cone structure is obtained shown in figure 3. From figure 4, the load vs. displacement curves shows the conventional ductile fracture with strain hardening and necking.
In Figure 5 (a) and 5 (b), load vs. displacement graph shows the material failed under brittle, necking zone is not visible and stain hardening is at minimal. Hence the elongation of Carburized and Carbonitrided specimen is 5% and 6% only.

![Figure 4. Load vs. Displacement – as received 16MnCr specimen.](image)

![Figure 5. Load vs. Displacement – (a) Carburized Specimen; (b) Carbonitrided Specimen.](image)

3.3. Case Depth

By finding the effective case depth of material after successful surface treatment, the hardness of the specimen decrease with distance penetrated from the surface. Figure 6 shows the case depth of surface-treated specimens. It is found that Carburized specimen with 720 HV in surfaces, when penetrated through the case has HV of 491 at 0.6 mm. However in Carbonitrided specimen surface has a relatively low hardness of 705.6 HV, when penetrated through the case has HV of 528.8. The Carbonitrided specimen exhibits bur formation in the fracture zone. Carbon influences the crack initiation and crack propagation by which yield strength of the material is increased up to 83.8 N/mm² and 57.8 N/mm² in Carburized and Carbonitrided specimen, respectively. The Carburized specimen’s
core has 370HV and Carbonitrided specimen has 330HV. The as-received specimen’s hardness is 230HV; hence an increase in hardness, carbon content prolongs the crack initiation and propagation and increases the maximum load-bearing capacity of the material.

![Case depth graph](image)

**Figure 6.** Case depth.

### 3.4. Hardness Test

Resistance for intending is measured by using the Rockwell hardness test. Carburized specimen has better hardness in both case and core. For consideration of 16MnCr5, diamond indenter is chosen as per Rockwell scale testing standards and hardness of the specimen is measured. The measurement is done on the C scale. The hardness values of as received, Carburized and Carbonitrided specimen are shown in Figure 7.

![Rockwell hardness graph](image)

**Figure 7.** Rockwell hardness.

### 4. Microstructural Observations

#### 4.1. Microstructure

Metallographic Test is used to analyze the microstructure of the specimen. The specimen is of length 20 mm and diameter 22 mm. The face of the material is polished using four grades of emery sheets to get finely polished outlook without a scratch. The specimen polished in a grinding machine with the addition of alumina. Then Nital, a mixture of 4% nitrogen and 96% of ethanol is applied partially to
face of the specimen and dried for 5 minutes. Then the specimen is placed under the optical microscope to obtain a clear microstructure.

The optical microscopic study of as received 16MnCr5 steel at 100X reveals ferrite and pearlite structures shown in figure 8, the proportion being found to be 83 % and 17 % respectively by applying lever rule method. The studies on after heat treatment also done at same 100X. As depicted in figure 9 (a), the Carburized specimen shows two different structures, a fine martensite on its case and a low carbon martensite on its core. The Carbonitrided specimen on the other hand, is with martensite structure at its surface, retaining austenite in traces and the core having same as that of Carburized specimen as shown in figure 9 (b).

4.2. Fractography

Observation on tensile fractured specimens characterizes the crack initiation and propagation of the Carburized and Carbonitrided specimen shown in Figure 10 (a) and 10 (b).
Figure 10. Fracture surface of – (a) Carburized tensile specimen; (b) Carbonitrided tensile specimen.

Scanning electron microscope images of fracture area of specimens are shown in Figures, 11 (a), 12 (a), 13 (a) and 14 (a) taken from Carburized specimens while figures 11 (b), 12 (b), 13 (b) and 14 (b) are taken from Carbonitrided specimen.

Figure 11. Fractography 1 mm – (a) Carburized tensile specimen; (b) Carbonitrided tensile specimen.

Figure 11 (a) and 11 (b) reveals the presence of inclusion-forming the case of the material. The fracture zone is shown in figure 12 (a) and 12 (b) shows visible fine faceted cleavages, the new crack nucleus is initiating from neared grains and propagate. Figure 13 (a), 13 (b) and Figure 14 (a), 14 (b) reveal the grain boundaries with dimple formation. Some regions are structure less because of slip band rupture and due to pulling force of the specimen underwent during tensile testing. The fracture found to be intermediate between ductile and brittle.
Figure 12. Fractography 50 μm – (a) Carburized specimen; (b) Carbonitrided specimen.

Figure 13. Fractography 100μm – (a) Carburized specimen; (b) Carbonitrided specimen.
However macro observations suggest that the case-hardened specimens are brittle fractured. When crack propagates from case to core reaching the grain boundary, the crack doesn’t propagate. It is because the core is retained with austenite where the case of the specimen is martensite because of surface treatment. But the fractograph images reveals cleavage and dimples in core spots of specimen results in an intergranular fracture.

5. Conclusion

16Mncr5 low carbon steels was surface treated by gas carburizing and gas carbonitriding process. Carbon enriches up to 0.600% of weight in the carburizing process and 0.494 % in the carbonitriding process. The Surface hardness of 59HRC is found in Carburized and 54 HRC in Carbonitrided specimen. The transformation from austenite to martensite in Micro structural changes were observed in both surface treated specimens. Reduction associated with volume expansion results when austenite transforms to martensite. The fracture mechanism in Carburized and Carbonitrided specimen study reveals that case exhibiting brittleness and core with ductility.

References

[1] André Luiz Vasconcellos daCosta e Silva, “The effects of non-metallic inclusions on properties relevant to the performance of steel in structural and mechanical applications”, Journal of Materials Research and Technology, Vol.8(2), pp.2408-2422, 2019, doi:10.1016/j.jmrt.2019.01.009
[2] P.Wang, S.P.Lu, N.M.Xiao, D.Z.Li, Y.Y.Li, “Effect of delta ferrite on impact properties of low carbon 13Cr–4Ni martensitic stainless steel”, Materials Science and Engineering: A, Vol.527(13–14), pp.3210-3216, 2010, doi:10.1016/j.msea.2010.01.085
[3] Chunfang Wang, Maoqiu Wang, Jie Shi, Weijun Hui, Han Dong, “Effect of microstructural refinement on the toughness of low carbon martensitic steel”, Scripta Materialia, Vol.58(6), pp.492-495, 2008, doi:10.1016/j.scriptamat.2007.10.053
[4] Hanamura, Yin Fuxing, Nagai Kotobu, “Ductile-brittle transition temperature of ultrafine ferrite/cementite microstructure in a low carbon steel controlled by effective grain size”, ISIJ international, Vol.44(3), pp.610-617, 2004.
[5] Wang Haojie, Bin Wang, Zhaodong Wang, Yong Tian, R.D.K. Misra, “Optimizing the low-pressure carburizing process of 16Cr3NiWMoVNbE gear steel”, Journal of Materials Science & Technology, Vol.35(7), pp.1218-1227, 2019, doi:10.1016/j.jmst.2019.02.001

[6] Atraszkiewicz R, B. Januszewicz, W. Stachurski, K. Dybowsk, A. Rzepkowski, “High pressure gas quenching: Distortion analysis in gears after heat treatment”, Materials Science and Engineering: A, Vol.558, pp.550-557, 2012, doi:10.1016/j.msea.2012.08.047

[7] Nandu Mohan, Sanjivi Arul, "Effect of Cryogenic Treatment on the Mechanical Properties of Alloy Steel 16MnCr5", Materials Today: Proceedings, Vol.5(11), Part 3, pp.25265-25275, 2018, doi:10.1016/j.matpr.2018.10.329

[8] Cm.Vivek, “Influence Of Carburizing and Carbonitriding in 16mncr5 to Enhance MechanicalProperties”, International Journal of Innovations in Engineering and Technology, Vol.7(3), pp.261-266, 2016.