Experimental investigation on microstructural and mechanical properties of quenched AISI 4145 sinter forged steel

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In the present investigation, microstructure and mechanical properties of sinter-forged AISI 4145 steel have been examined. Homogeneous powder blend of steel corresponding to AISI 4145 composition has been taken to prepare the compacts of 30 mm diameter with 1.0 aspect ratio on hydraulic press using suitable die assembly. Protective coated green compact preforms have been sintered at 1150 °C ± 10 °C for a period of 90 min. Subsequently, the sintered preforms have been hot upset forged to square cross-sectional bars (~13 mm × ~13 mm) with the length of 110 ± 5 mm. Further, the bars have been quenched in oil with and without homogenisation. Mechanical properties such as tensile strength, yield strength, percentage elongation, and impact strength have been analysed. Optical microscopy (OM), scanning electron microscopy (SEM) and X-ray diffraction (XRD) studies have been used to characterize the metallurgical features of the steel on different oil quenched condition. Microstructure reveals the ferrite, pearlite and non-equilibrium martensite structures in the sinter-forged low alloy steel. Sinter forged steel exhibits enhanced strength and hardness in homogenized oil quenched condition.

Keywords: Sintering, Forging, Low alloy steel, Oil-quenching, Homogenization

1 Introduction

Mechanical properties such as tensile strength, impact strength, hardness and ductility are the important design features for selection of materials for specific applications in automotive, aerospace and other industries. Excellent strength, ductility, toughness, formability and weld ability are the major benefits of the low alloy steels. The production of these steels for making structural parts for higher strength levels emerged due to their benefits1. Due to their excellent properties, AISI 41XX steels find their applications in petroleum and gas industry2. Particularly AISI 4145 steels are used in aerospace industry and off-shore plat forms, ships and pressure vessel. Further, producing low alloy high strength steel through powder metallurgy route is an attempt to make parts in a cost effective manner over conventional processes. The parts made by this route have shown comparable mechanical properties to cast and wrought products3-6. Many components such as connecting rod, automotive transmission parts are replaced by powder forged products7,8. Powder preform forging also has an advantage of property enhancement, material usage, time and cost saving at higher rate of production9. Part production by powder forging, involves the fabrication of a preform by conventional powder metallurgy and then forged to its final shape with substantial densification10.

Powder preform forging (or) sinter forging is an effective and established method to improve density and produce high strength structural parts with improved mechanical properties11. The mechanical properties of the powder metallurgy products depend on the densification. It is also reported that mechanical properties of the powder metallurgy products can be enhanced by heat treatment called sinter-hardening process. In which, the sintered specimens can be cooled rapidly after sintering to enhance the mechanical properties to desirable applications12. The sinter hardening of the ferrous powder metal products improves the strength and hardness by forming martensite and bainite. Many investigators worked on the sintered steels to improve their strength and hardness by sinter hardening process13-16. The heat treatment after powder forging is the novel approach to develop the powder forged steels with higher mechanical properties.

An attempt has been made in the present investigation to produce low alloy AISI 4145 steel by
using elemental powders through sinter-forging technique and to evaluate the micro-structure, mechanical properties of low alloy AISI 4145 steel under different oil quenching conditions.

2 Experimental Procedures

The elemental powders of iron, graphite, silicon, manganese, chromium, and molybdenum were used in required proportion as shown in Table 1. The atomized iron powder size of -180 µm was procured from M/s. Sundaram Fastners Ltd., Hyderabad, India. The other alloying elemental powders, such as graphite, manganese, silicon, chromium and molybdenum of -37µm in size were procured from M/s. Ghrishma Speciality Powders, Mumbai, India.

Elemental powder mixture of AISI 4145 steel was taken in a stainless steel pot along with the ceramic balls with ball to powder mix ratio of 1:1. Pot mixing operation was run for 32 h to prepare homogeneous powder blend. The absolute density of the AISI 4145 steel composition was 7.7057 g/cc. Homogeneity of the powder blend was ascertained by measuring the flow rate, and apparent density. Apparent density and flow rate of powder blend were shown in Table 2.

The cylindrical compacts of powder blend AISI 4145 steel were prepared on 1.0 MN capacity hydraulic press using suitable die assembly to produce samples of 30 mm diameter with aspect ratio of 1:1. The green density of compacts was maintained with the relative density of 85±1 (6.55 g/cc approximately) percent theoretical density by applying pressure 480 ± 10 MPa. The prepared compacts were coated with the indigenously developed ceramic coating in order to protect them during sintering operation. The ceramic coated compacts of steel were sintered in an electric muffle furnace at 1150 ± 10° C for 90 min. After sintering, the compacts were immediately forged to square cross-section (~13mm ×~13mm) bars of approximate length of 110 ± 5 mm from cylindrical billets on a 1.0 MN capacity friction screw press at 1150 ± 10° C with multiple passes. The relative density of the specimens was increased up to 99.4% of theoretical density by forging process. Subsequently, after sinter forging operation, one set of the forged bars was directly quenched in oil and same was categorized as oil quenched (OQ). Further, the set of forged bars was homogenised in the furnace for a period of 60 min, and then quenched in oil and they were termed as homogenized oil quenched (HOQ). The OQ and HOQ forged bars were cleaned and machined to standard specimens for impact and tensile testing. Tensile tests were conducted on electro-mechanical controlled Hounsfield Tensometer as per ASTM E8M standards. The test was performed on three samples and average value was mentioned. The impact tests were conducted on Izod Impact Testing Machine without notch according to ASTM D256 standard. Hardness measurement was carried out on Rockwell hardness tester on HRc Scale. Metallographic samples were polished using conventional polishing technique and then etched with 2% nital solution. Light optical microscope with image analyze software was used to capture the microstructure to analyze the morphology of the different oil quenched specimens. X-ray diffraction (Rigaku - Ultima III, Japan) technique was used to identify the phases of the sinter forged steel. The scanning electron microscopy (SEM) was used to study the fractography of the fracture surface of the tensile tested specimens.

3 Results and Discussion

3.1 XRD characterization

The X-ray diffraction patterns for OQ and HOQ specimens are shown in Fig. 1. The sinter-forged AISI 4145 steels exhibits the XRD pattern corresponding to the crystal structure of body centered cubic structure with diffracted planes of (110), (200), (211).

During cooling a small fraction of austenite remains in the material and termed as retained...
austenite (RA). The presence of retained austenite is indicated by (111), (200) peaks in the quenched steels. The low intensity of these (111), (200) peaks represents the low amount of retained austenite in the present sintered forged steel. The faster cooling will not give time to diffuse the carbon atoms, from austenite to form cementite and ferrite, but they are trapped in the octahedral sites of a body-centered cubic structure. The alloy composition and material processing parameters are the major factors to retain austenite in low alloy steels. Austenite stabilizers improve the formation of retained austenite in the low alloy steels. The presence of manganese, silicon and carbon improves the austenite retention during the transformation. The formation of pearlite, ferrite, retained austenite and martensite in OQ specimens occurred due to cooling of the specimens at lower temperature than HOQ specimens. The temperature is lowered during forging operation in OQ specimens, which leads formation of equilibrium phases like ferrite and pearlite before quenching where as reheating to 1150 ± 10 °C for homogenization of HOQ specimens helps to relieve the stresses induced during forging and uniform property throughout the material before quenching operation was done. Therefore, HOQ specimens formed non-equilibrium phase of martensite due to quenching from 1150 ± 10 °C. Even though both were oil quenched, the temperature difference between OQ and HOQ varies the cooling rate.

3.2 Mechanical properties
The mechanical properties of the OQ and HOQ of AISI 4145 PM steel specimens such as ultimate tensile strength (UTS), yield strength (YS), % elongation (% EI), hardness and impact strength are calculated after testing the specimens.

3.3 Tensile properties
The stress-strain curve for the sinter-forged AISI 4145 steels of OQ and HOQ conditions are shown in Fig. 2(a). The tensile strength and elongation of the sinter forged AISI 4145 steels of OQ and HOQ conditions are shown on bar charts in Fig. 2(b) and 2(c), respectively.

The high tensile strength of 1123 MPa is obtained in HOQ specimen as compared to OQ specimens. Even though both are oil quenched, but at which temperature it quenched influences the cooling rate and microstructural features of the specimens. The OQ specimens directly quenched immediately after forging, which reduce the temperature transmission as compared to HOQ specimens. The low temperature transmission and strain induced in the material caused to form complex microstructure containing the martensite and pearlite/ferrite along with the retained austenite in the OQ specimens. The presence of the pearlite increased the ductility of the OQ specimens as compared to HOQ specimens. While the homogenization at 1150 ± 10 °C for 1 h reveals the
stresses induced during forging and enhances the homogeneous structure in the microstructure. The cooling of HOQ specimens occurred at high temperature as compared to OQ specimens due to reheating, which increased the amount of martensite and thereby increased the tensile strength of the specimens. Thus, material processing and cooling rate greatly influence the mechanical and microstructural properties of the materials.

3.4 Hardness and impact strength

Hardness and impact strength of the sinter forged AISI 4145 steels of OQ and HOQ conditions are shown in Fig. 3. Figure 3 shows the increment in the hardness in the order of OQ to HOQ condition, whereas decrease of impact strength in the same order. The increase in the hardness in HOQ condition specimen reveals that the cooling rate and microstructure have influenced the hardening of the steel. The faster cooling in low alloy steel produces grain refinement and formation of martensite. When cooling rate is high, carbon atoms cannot diffuse in the austenite to form equilibrium microstructure of pearlite/ferrite matrix due to lack of time, and forms non-equilibrium microstructures like martensite. The lattice distortion occurs during the formation of martensite from austenite and this distortion in the material stop the dislocation movement of atoms thereby increased the strength and hardness. The tensile properties also witness that the strength is increased in HOQ specimens as compared to OQ specimens. Even though both are oil quenched, the temperature difference between OQ and HOQ while quenching varies the cooling rate. The OQ specimens directly quenched immediately after forging, whereas HOQ specimens are reheated to 1150 ± 10° C and then quenched, which reduce the temperature transmission as compared to HOQ specimens. The faster cooling rate produces the martensite in HOQ condition specimens, and thereby increase the hardness compare to OQ condition specimens, whereas impact strength pattern is observed reciprocal to the hardness in the quenched steels. The volume fraction of martensite in both conditions varies the hardness of sinter forged low alloy steel. The presence of ferrite and pearlite matrix greatly influences the impact strength of the OQ condition specimen and attained high impact strength of 79 J. Thus, the hardness and impact strength of the sinter forged low alloy steel are good agreement between cooling rate and microstructure.

3.5 Microstructure analysis

The optical microstructures of specimens of corresponding to OQ and HOQ conditions of sinter-forged AISI 4145 steels are shown in Fig. 4 (a, b),...
respectively and the scanning electron micrographs of the above conditions are shown in Fig. 5 (a, b), respectively. Since the OQ specimens quenched after forging, the stress induced in the material and temperature drop during forging play a major role while determining the microstructure. Due to deformation induced during forging, fine and medium sized grains are observed in OQ specimens, and the temperature decreases during the forging before quenching process produces complex microstructure containing ferrite, pearlite along with retained austenite. The grain refinement in low alloy steel through heat treatment process increases the mechanical properties. SEM micrograph (Fig. 5(a)) of OQ samples clearly show the phases present in the oil quenched steel.

Figures 4(b) and 5(b) show the optical and SEM micrographs of HOQ specimens, respectively. It shows the martensite along with retained austenite in the sinter forged low alloy steels. The HOQ specimens are quenched after homogenization at 1150 ± 10°C for 1 h in the furnace after forging, which helps to relieve the stresses induced during the forging in the material and forms uniform distribution of grains. The HOQ specimen shows higher amount of martensite phase, this is due to cooling from high temperature than OQ specimens. Since these specimens are quenched from 1150 ± 10°C to room temperature rapidly by quenching in oil, faster cooling rate increases the formation of martensite in low alloy steels. The martensite phase in low alloy steels improves the strength and hardness of the material. The higher cooling rate reduces the diffusion of carbon in iron and forms non-equilibrium structures like bainite and martensite in the low alloy steels. The presence of chromium and molybdenum reduces the diffusion of carbon in iron in low alloy steels, which enhances the formation of martensite in low alloy steels.

3.6 Fractographic analysis

The scanning electron microscopy (SEM) fractographs of different oil quenched AISI 4145 steel specimens are shown in Fig. 6 (a, b). Figure 6(a)
shows the fractograph of sintered forged subsequently oil quenched (OQ) and it shows more ductile mode of fracture and less cleavage fracture. Fine dimples observed at many places and also particle pull-off is clearly observed. The presence of pearlite and martensite influenced the nature of fracture during the testing. The soft pearlite matrix increases the ductile mode fracture, whereas the martensite influences the particle pull-off during the fracture. The presence of fine cracks and voids in the fractograph are also observed. Thus it indicates mixed mode of failure in OQ specimens which is mainly ductile and partially brittle mode failure. The microstructural features and ductility of the materials also confirm the mixed mode of failure.

Fracture surface of tensile tested sintered forged homogenized oil quenched (HOQ) steel is shown in Fig. 6(b), which exhibits more cleavage facets with brittle mode of failure with localized plastic deformation. The presence of the martensite increases the brittle mode of fracture, whereas retained austenite caused the localised deformation. Particle delamination is observed in HOQ specimens, which resulted in low values of percentage elongation as compared to OQ specimens. The presence of cleavage pattern in HOQ specimen fractograph is more predominant and very small amount of dimples and voids have been observed. Thus it indicates mainly brittle mode of fracture with less ductility in HOQ specimens. The correlation between microstructure and mode of failure of the differently oil quenched specimens best suited for given mechanical properties.

4 Conclusions
(i) The high strength low alloy AISI 4145 steels were developed through sintered-forged process from elemental powders.
(ii) Quenching the specimens with and without homogenization has influenced the properties of AISI 4145 sinter forged steels.
(iii) Homogenized oil quenched specimens shown the high strength and hardness as compared to direct oil quenched specimens.
(iv) The non-equilibrium structures like martensite pockets were observed in both oil quenched specimens. Structure-property correlation for the quenched samples well corresponded.
(v) The fractography analysis shows brittle fracture in HOQ specimens and mixed mode of failure in OQ specimens. The ductility and toughness associated with the fracture surfaces were well corresponded.

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