Toughness study of Borided, Borided and induction modified AISI 4340 steel

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Abstract. In this study, pack boriding is done on AISI 4340 steel in steel containers for 3 hours at 950°C. Boriding results in the formation of FeB or Fe2B columnar microstructure at the case. Such microstructure brings about a high brittleness of the boride layer. Induction surface modification is done on Borided samples to bring down the surface hardness. We put an effort to enhance the toughness of boride layer using 30 kW power high frequency induction heat source. The toughness of borided, borided and induction surface modified specimens are evaluated by shear punch test. Cylindrical punch of 4 mm diameter is used in this test. The toughness is calculated from the load-displacement curve. Induction modified specimens exhibit 38% improvement in toughness as compared with borided specimens. This improvement in toughness may be due to blunting of acicular boride structure in to a globular structure at the interface, smooth hardness gradient and formation of single phase Fe2B microstructure as a result of induction surface modification.

1. Introduction

The AISI 4340 is a low alloy steel, widely used as a material for manufacturing of different types of gears, shafts owing to the exceptional combinations of good mechanical and fatigue properties [1]. However, this steel has inadequate surface hardness when it is used in tribological applications [2]. Thus, its surface modification is necessary to improve the hardness. Boriding is one of the capable surface modification techniques to produce very hard surfaces on steels [3-4]. Boriding on steels can offer higher surface hardness (1400 – 2100 HV), as compared to carburizing (700 – 850 HV), nitriding (600 – 1100 HV) and carbo-nitriding (940 – 1000 HV) [5]. Borided steels offer wear resistance analogous to that of sintered carbides [6].

As Boriding on steels can be done through different methods like pack, molten salt and gas boriding [7-8]. This process is carried out in the temperature range of 700°C to 1000°C for 1-12 hours in the presence of suitable boriding mixture [9-10]. During this process distribution of boron into the surface of the steel takes place, two phase microstructure (Fe2B and FeB) and superficially, directional saw tooth microstructure is framed [11]. Eyre [12] reported that Fe2B and FeB phases formation based on the boron potential. If the boron potential is 8.83%, Fe2B phase only forms in the case; at 16.3% of boron, FeB phase also forms over and above Fe2B. The Fe2B phase forms nearby to the core and the FeB phase forms in close proximity to the surface. Two phase microstructure (FeB+Fe2B), pores in the case, anisotropic distribution of boron in the case, high process time, high process temperature result...
in poor toughness and ductility [13]. The effective use of borided components is restricted due to high brittleness.

For improving the toughness of the boride layer or/and borided steel, several kinds of surface engineering techniques have been tried by the researchers. The full disappearance of FeB layer is observed as a result of post diffusion annealing on borided steels, by heating the borided steels at 950°C for 6-8 hours [14-16]. Multicomponent boriding is suggested as one of the effective method to enhance the toughness of borided steels by carefully choosing the alloying elements such as copper, aluminium, chromium, silicon and nickel along with diffusion of boron [17-19]. Superplastic boronising is reported as an effective method to result in equiaxed boride grains with high toughness [20-24]. However, this is comparatively harder technique to be used for standard engineering components. Interrupted boriding is suggested as another alternative method to enhance the toughness and ductility of borided steels with fewer disturbances to the core [25]. Laser surface modification of as-borided steels results in significant improvement in the toughness due to the formation globular microstructure and better hardness gradient [26]. By doing laser treatment, surface hardness decreases and simultaneously toughness and ductility increases appreciably by reducing the degree of non-uniformity of the borided layer and generating residual compressive stresses [27].

In this investigation, an attempt is made to study the improvement in toughness of borided 4340 steel using induction surface modification.

2. Experimental details
2.1. Base Material
A medium carbon low alloy steel (0.39 C, 1.4 Ni, 0.8 Cr, 0.6 Mn, 0.3 Si, 0.4 Mo, balance Fe) is used as a base material (AISI 4340) for boriding. The steel specimens are normalized before boriding. The steel has a hardness of 449±5 HV (at 100 g load). Specimens of 12 mm diameter and 0.6 mm thickness are used for shear punch test.

2.2. Boriding and Induction surface modification
Boriding is done on AISI 4340 steel sheets of 18 mm diameter, 0.600 mm thickness using pack process (paste method) in a furnace at 950°C for 3 hours.

The borided surfaces are modified using 30 kW power high frequency induction heating machine. The gap between the coil and specimen is kept constant as 3.5mm. The input voltage is kept constant as 210V. The induction coil is fixed stationary. The specimens are moved at four different feed rates. A protective paste is applied on the exterior (surface) of the specimen to avoid oxidation.

After this treatment, the specimens are studied metallographically. The microstructures are observed using Zeiss axiovert optical microscope at suitable magnifications. The microhardness along the case was measured using Mitutoyo microhardness tester at a load of 100 g. The phase analyses are carried out using Shimadzu X-ray diffractometer, using Cu Kα radiation. The toughness of borided, borided and induction surface modified specimens are evaluated by shear punch test using small specimen of about 18 mm diameter and 0.6 mm thickness as per ASTM D732-10. The shear punch test is performed on a computerized materials testing system (FINE Testing Industries, Model TFNP 25KN) with a load cell of 25 kN capacity and an optical encoder with 1000 pulse per minute for uninterrupted monitoring of the applied load and a data acquisition system measuring punch head displacement. The shear punch experimental setup utilizes a flat cylindrical punch of about 4 mm in diameter. The load on the punch is calculated as a function of the punch journey and the graph of load vs. displacement is made. The material selected for both the die and punch is A2 air hardened tool steel (RC 58).
3. Results and discussions

The optical microstructure of borided specimen is shown in Figure 1. The microstructure shows typical two phase (Fe$_2$B – FeB) acicular boride needles for an average length of 100 µm.

![Figure 1. Optical microstructure of borided AISI 4340 steel.](image1)

The above figure 2 (a-d) give details an optical microstructures of borided and induction modified specimens treated at feed rates of 8.7, 9.7, 10.5, 11.5 mm/s. It is found that induction surface modification of borided specimens treated at a feed rates less than or equal to 9.7 mm/s results in the deterioration of the case microstructure. Figure 2 (c & d) show the improved modification of the case with increasing feed rates, with apparent sign of rounding of acicular boride needles at the interface.

![Figure 2. Optical microstructures of borided and induction modified steel at different feed rates, (a) 8.7 mm/s; (b) 9.7 mm/s; (c) 10.5 mm/s; (d) 11.5 mm/s.](image2)
resulting in possible improvement of toughness of boride layer. It is observed that by increasing the induction power, acicular nature of boride layer disappears significantly. The compactness of the boride layer increases with increase in induction power. Figure 2 (d) also demonstrate the development of spherical boride particles proximity to the surface. The average case depth of induction modified specimen treated at 11.5 mm/s was 72 µm. The case depth decreases may be due to dilution of boron from case to core. Further, it is apparent from the present investigation that a minimum feed rate of 11.5 mm/s is necessary to cause effective microstructural modification. Characteristic directional growth of the thermo-chemical diffusion based treatment vanished due to induction treatment as similar like laser treatment [27].

![Figure 3. XRD pattern of borided specimen.](image)

Figure 3. shows XRD pattern of borided specimen. XRD pattern illustrates the presence of Fe₃B and FeB phase in the borided case. This two phase boride microstructure exhibits inferior mechanical properties as reported by many researchers [3, 6, 11 and 13].

![Figure 4. XRD Pattern of borided and induction modified specimen at a feed rate 11.5mm/s.](image)

Figure 4 shows XRD pattern of induction modified specimen treated at a feed rate of 11.5 mm/s. The absence of hard brittle phase (FeB) has been observed from the XRD pattern. XRD pattern explains the presence of single phase Fe₃B in the induction modified surface. The single phase Fe₃B microstructure exhibits better ductile behavior as compared with dual phase microstructure as reported by many researchers [3, 6, 11 and 13].
Figure 5. Microhardness profiles of borided, induction modified at a feed rate of 11.5 mm/s.

The above figure 5, shows the microhardness profiles (ASTM E384) of the borided specimen and borided and induction modified specimen with feed rate of 11.5 mm/s. The average peak surface hardness measured from borided specimen is 1700 HV. This peak surface hardness is caused by the presence hard FeB phase present on the case. The microhardness is observed in the range between 800 HV – 1700 HV approximately. There is a great variation in the microhardness of the borided case indicates greater inhomogeneity of boron distribution in the case. The average peak surface hardness of induction modified specimen is 1100 HV. The micro hardness is found to vary between 1000 HV – 1100 HV approximately. Microstructural refinement due to induction modification results in better distribution of boron and other alloying elements in the case. The decrease in surface hardness and less scatter in hardness across the section are due to effective homogenization happened during induction modification.

Figure 6. A comparison of load vs punch displacement plot from a shear punch test of borided specimen and borided, induction modified specimen treated at 11.5 mm/s.

The mechanical properties such as ductility, strength and toughness of borided and borided and induction modified were estimated from the load-displacement curve shown in the figure 6. The shear
punch test is preferred method for the evaluation of mechanical properties of thin coatings. Shear punch test is based on blanking process, consisting of clamping a small thin sheet between the die and punch [26].

It is found that induction modification is the cost effective method to break down the acicular needle of conventionally borided steel as compared to laser modification. Borided and induction modified specimens exhibit lesser tensile strength as compared to the only borided specimens. The strength of the induction modified borided specimen is lowered be due to drop in the surface hardness. The notch angle between boride layer and iron substrate in the case of conventional boriding is around 90⁰C. It is observed from the optical microstructures that induction modification results in reducing the notch angle significantly. Because of reduction in notch angle, toughness is improved significantly. 38% improvement is estimated from the shear punch curve.

4. Conclusions
Acicular microstructure is replaced by globular microstructure in the induction surface modified borided AISI 4340 steels. Due to effective homogenization, lesser hardness scatter is observed. Such lesser hardness gradient leads to single phase of Fe-B microstructure on the surface. Thus, toughness in induction modified boride steel is enhanced by 38%.

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