COMPARATIVE EVALUATION OF ABRASIVE WEAR RESISTANCE OF VARIOUS STAINLESS STEEL GRADES

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ABSTRACT

Stainless steels are widely used materials due to their excellent corrosion resistance properties. Martensitic stainless have added advantage of higher hardness / strength over other stainless steels. Because of higher hardness, martensitic stainless steel grades are also used for applications involving abrasive media. However, relative data on wear resistance of stainless steels is not available in open literature. In view of this, abrasive wear studies on stainless steel grades AISI 420, AISI 440C, CA6NM (13Cr-4Ni) and 17-4PH (AISI 630) have been conducted using a dry/sand rubber wheel test according to standard ASTMG65. Samples of all grades were heat treated to obtain desired hardness values and then abrasive wear tests were carried out. Silica quartz sand in size range of 211 to 297 μm was used as an abrasive medium. Samples were characterized for all relevant properties before wear test and evaluated for wear pattern of surface after wear test using optical and scanning electron microscope. It is observed that AISI 440C possesses highest abrasive wear resistance among the four grades investigated.

KEY WORDS: Abrasive wear, ASTM G65, Heat treatment, Stainless steel

1. INTRODUCTION

Wear is an important parameter for selecting materials operating in wear prone environments [1, 2]. Wear can be classified based on mechanism involved, interaction between the surfaces and medium used [3, 4]. In abrasive wear, hard particles or material asperities scratch one of the surfaces, the particles or asperities are called abrasives. Abrasives carry at least some of the load between the two surfaces. In two body abrasion, the abrasives are fixed to one of the surfaces and cause scratching of the other surface. Lot of parallel scratches are formed on the surface in this situation. In three-body abrasion, foreign loose particles or debris of abrading material are present between two surfaces. These abrasives slide and roll between the surfaces. Pits and parallel scratches are usually observed in wear patterns. Sometimes the abrasives are embedded into the softer surface and later cause two-body abrasion on the harder surface [5]. The dry sand/rubber-wheel abrasion test is commonly used to evaluate low-stress abrasive wear of materials, extensively used to evaluate wear-resistant materials used in the mining, oil sand, oil pipe lines and agricultural machinery industries. In The dry sand/rubber-wheel abrasion test, a specimen is loaded against the rim of a rotating rubber wheel; a sand flow is directed to the gap between the wheel and specimen, sand abrades the specimen under an applied normal load. Weight loss is used to calculate volume loss. Volume loss used to determine abrasion resistance of a material [6]. Mechanisms; ploughing, cutting or brittle fracture are observed in abrasive wear [7-9]. The wear rate depends extensively on chemical composition [10], microstructure [11], the surface properties [12] of the material and the ambient conditions and experimental parameters such as applied load, sliding distance and operational conditions [13-15]. For many industrial applications, the rubber-wheel test is performed often under a fixed load and at a fixed sliding speed to have all tested materials evaluated under the same condition. ASTM G65 has specified such abrasion test with fixed loads and fixed sliding speeds for ranking materials in different classes. It must be pointed out that whenever there is a possibility of abrasive wear, it is the most important problem to be solved since this is the mechanism that determines the removal rate. Wear of machinery leads to additional maintenance costs and a reduction in productivity [16]. Martensitic stainless steels are commonly used for manufacturing components with excellent mechanical properties and moderate corrosion resistance, so that they can work at high and low temperatures. Unlike other stainless steels, their properties can be changed by heat treatment; hence these steels usually are used for a wide range of applications like steam generators, pressure vessels, mixer blades, cutting tools [17–19]. The typical heat-treatment sequence for martensitic stainless steels includes austenitizing to form an austenitic structure and fully or partially dissolve carbides, cooling or quenching to transform the austenite to martensite, followed by tempering of the martensitic structure to improve toughness and ductility. The volume fraction and size of the carbide particles present in the steel play a major role in determining the hardness, strength, toughness, corrosion resistance, and wear resistance of the steel [20]. Stainless steels containing high chromium (11-18%) and carbon (0.3-0.4%) are preferred when high wear resistance and sharp cutting surfaces are required [21].

The present investigation aims to study four stainless steel grades AISI 420, AISI 440C, CA6NM (13Cr-4Ni) and 17-4PH (AISI 630) in terms of their chemical composition, microstructure, hardness and abrasive wear resistance.

2. EXPERIMENTAL WORK

The experimental portion of this study includes optical microscopy, heat treatment, hardness measurement and abrasion test.

2.1 Materials

The chemical compositions of the stainless steels used are presented in Table 1. AISI 420, 440C and 17-4PH were acquired in form of forged rods. AISI 420 and 440C were received in annealed condition. CA6NM was received in form of cast block. From the received materials, 76 x 26 x 12 mm size samples were prepared, which is standard sample size requirement for abrasion test ASTM G65.

TABLE 1: CHEMICAL COMPOSITION ANALYSIS (wt %, BALANCE Fe)

2.2 Heat treatment

AISI 420, AISI 440C and CA6NM were hardened by quenching in oil and tempering. All grades were austenitized for 30 min and then quenched in oil. Tempering was followed after quenching. Samples were tempered for 30 min, followed by air cooling. 17-4PH was solutionized and aged. Heat treatment carried out for all grades is shown in table 2.

TABLE 2: HEAT TREATMENT

2.3 Abrasion test

Abrasion test is performed using an apparatus based on ASTM G65-00 test standard [22]. Fig 1 shows a schematic diagram of the abrasion test equipment [23]. Layer of Chlorobutyl rubber is mounted on mild steel wheel. Silica quartz sand is used as abrasive in size range of 211 to 297 µm, which is shown in Fig 2. Feed rate of abrasive sand is 250-300 gm/min. 200±10 rpm rotational speed of rubber wheel is maintained during all the tests. Load is kept constant at 130.5 N for all the samples. Procedure E of ASTM G 65-00 was followed for each test. Each sample is tested for 1000 revolution of rubber wheel. After each test, the samples are cleaned and then weighed. The abrasion test results are reported as volume loss in cubic millimeters.

$$Volume\ loss(mm^3) = \frac{Weight\ loss\ (gm)}{Density\ (gm/cm^3)} \times 1000$$

FIGURE 1: SCHEMATIC OF DRY SAND/RUBBER WHEEL ABRASION TEST SET-UP

FIGURE 2: SEM IMAGE OF SILICA QUARTZ PARTICLES AT 35X

3. RESULTS AND DISCUSSION

3.1 Metallographic examination

Metallographic examinations on heat treated samples were carried out using optical microscopy. Vilella's reagent (consisting of 1 g picric acid, 10 ml hydrochloric acid, and 100 ml ethanol) was used to reveal the general microstructure. AISI 420 shows tempered martensitic microstructure as shown in Fig 3 and SEM image in Fig 4. Note that Platelet type of martensite morphology is observed in SEM image of AISI 420. Because of low carbon content, no carbide formation is observed.

FIGURE 3: OPTICAL METALLOGRAPH OF AISI 420 (MAG.200X)

FIGURE 4: SEM IMAGE OF AISI 420 (MAG.2500X)

AISI 440C is high carbon martensitic stainless grade. In Fig 5, microstructure of AISI 440C grade is shown. Carbides in martensitic matrix are observed. Carbides and martensitic matrix impart high hardness to AISI 440C. Carbides in AISI 440C are M_7C_3 and $M_{23}C_6$, where M can be Cr, Fe, Mo and V. Carbides were studied using EDS (Fig 6). Table 3 shows that high amount of Chromium, Vanadium, Manganese and Iron are present in the carbides. Spheroidal carbides are M_7C_3 carbides and elliptical carbides are

$M_{23}C_6$ carbides. $M_{23}C_6$ chromium rich carbides are dissolved at the austenization temperature (~1150° C) and precipitate only after the tempering process [24]. As austenizing temperature was below 1150° C, $M_{23}C_6$ carbides were not completely dissolved. $M_{23}C_6$ carbides were present after quenching.

FIGURE 5: OPTICAL METALLOGRAPH OF AISI 440C (MAG.1000X)

FIGURE 6: CARBIDE EDS ANALYSIS IN GRADE AISI 440C

TABLE 3: RESULT OF EDS ANALYSIS OF AISI 440C

CA6NM has tempered martensitic microstructure as shown in Fig 7. CA6NM microstructure consists fine tempered lath martensite.

FIGURE 7: OPTICAL METALLOGRAPH OF CA6NM (MAG.200X)

17-4PH has martensitic microstructure which is shown in Fig 8. SEM (Fig 9) shows presence of intermetallics. 17-4PH is strengthened and hardened by precipitation of Cu-rich spherical particles in the martensite (α) matrix. Precipitates are not observed in optical metallograph or SEM image because these precipitates have dimensions below the resolution of optical microscope and SEM.

FIGURE 8: OPTICAL METALLOGRAPH OF 17-4PH (MAG.200X)

FIGURE 9: SEM IMAGE OF 17-4PH (MAG.1000X)

3.2 Wear Test Data

Hardness measurements were carried out using Rockwell hardness tester. Hardness values of all grades are given in Fig 10 after heat treatment. After quenching and tempering heat treatment, very high hardness was achieved in AISI 440C.

FIGURE 10: HARDNESS VALUES OF ALL GRADES AFTER HEAT TREATMENT

AISI 440C has higher hardness due to higher Carbon, Chromium, Molybdenum and Vanadium. AISI 420 achieved second highest hardness. 17-4PH achieved maximum hardness after aging treatment. Wear test data are given in Table 5.

Volume loss of all grades is shown in Fig 11. Fig 12 shows wear test samples.AISI 440C shows minimum volume loss while CA6NM shows maximum volume loss. In abrasive wear, the microstructure of material has significant importance. Better abrasion resistance in AISI 440C is attributed to carbides and martensitic matrix. Carbides in AISI 440C reduce material removal from surface by mechanisms like ploughing, cutting or brittle fracturing.

Table 5: Hardness, Density, Weight loss and volume loss of heat treated samples

FIGURE 11: VOLUME LOSS OF TESTED GRADES

4. CONCLUSIONS

The wear resistance of various heat treated stainless steel grades has been investigated as per ASTM G 65 - 00. The conclusions drawn are as follows:

- Based on the volume loss data obtained for AISI 420, AISI 440C, CA6NM and 17-4PH are 190, 24, 351 and 300 mm^3 respectively, AISI 440C has lowest volume loss implying maximum abrasion resistance while CA6NM has maximum volume loss implying minimum abrasion resistance.
- Lowest volume loss of AISI 440C can be correlated to the martensitic matrix of high hardness and presence of hard carbides in martensitic matrix.
- Highest volume loss of CA6NM can be correlated to its low hardness.
- The results clearly indicate that the microstructure and hardness has significant influence on the wear resistance.

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Figures

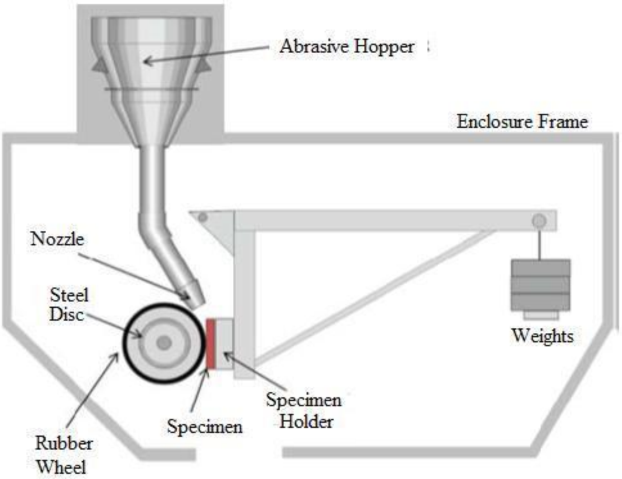

FIGURE 1: SCHEMATIC OF DRY SAND/RUBBER WHEEL ABRASION TEST SET-UP

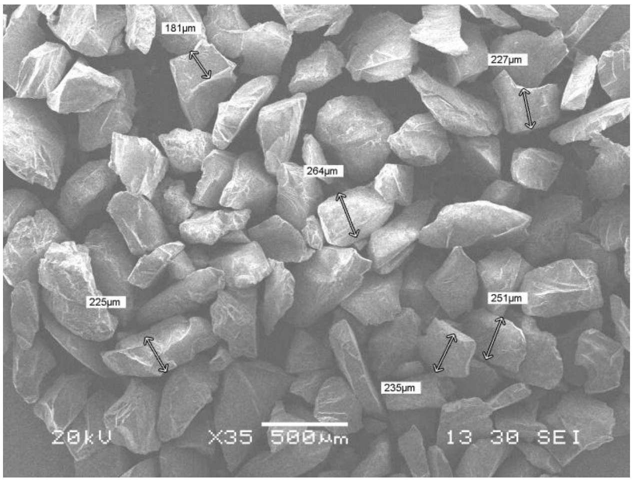

FIGURE 2: SEM IMAGE OF SILICA QUARTZ PARTICLES AT 35X

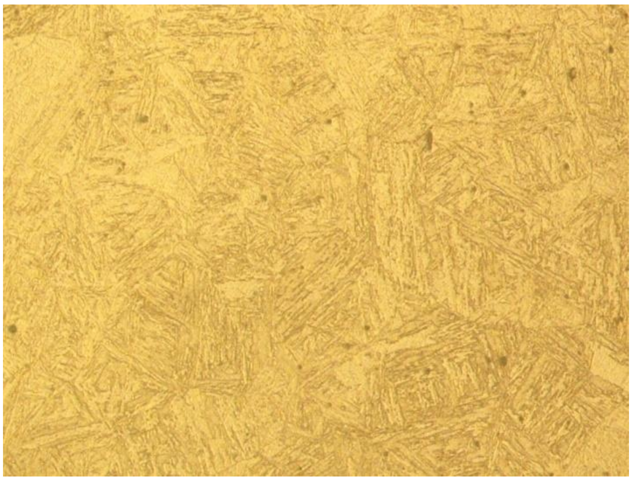

FIGURE 3: OPTICAL METALLOGRAPH OF AISI 420 (MAG.200X)

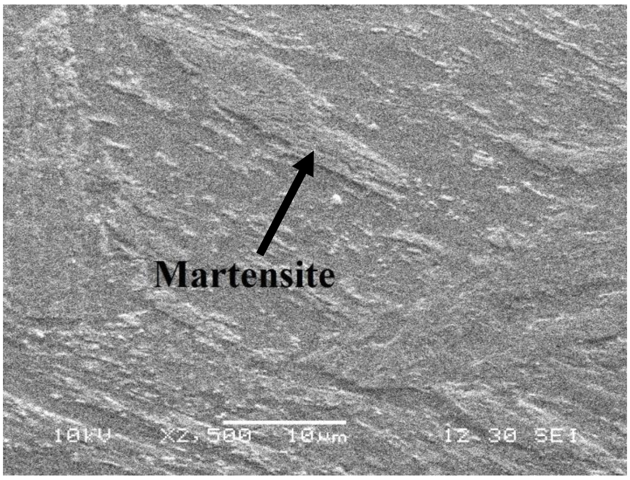

FIGURE 4: SEM IMAGE OF AISI 420 (MAG.2500X)

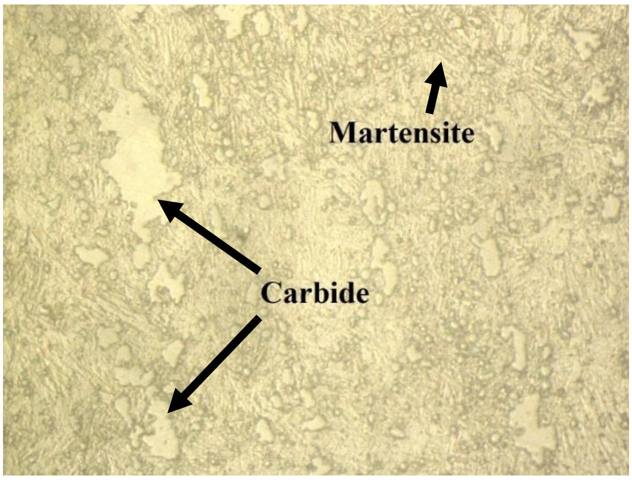

FIGURE 5: OPTICAL METALLOGRAPH OF AISI 440C (MAG.1000X)

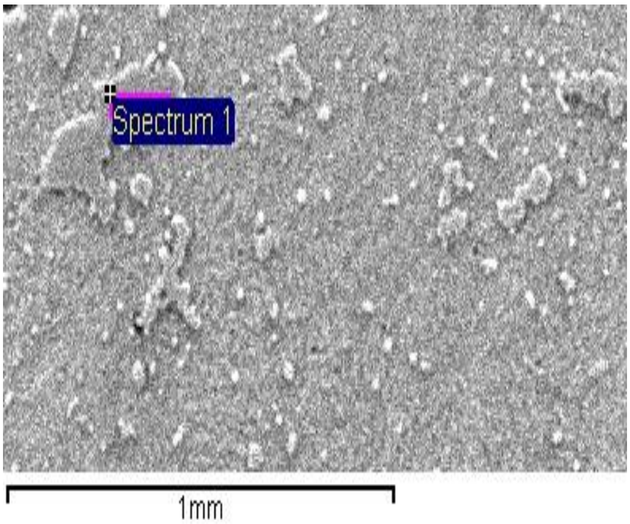

FIGURE 6: CARBIDE EDS ANALYSIS IN GRADE AISI 440C

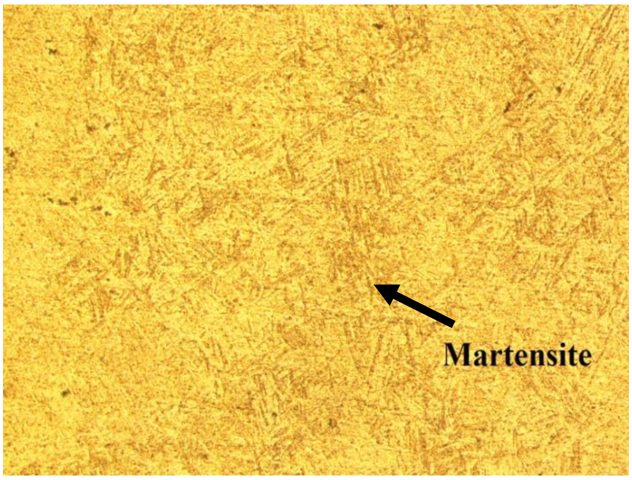

FIGURE 7: OPTICAL METALLOGRAPH OF CA6NM (MAG.200X)

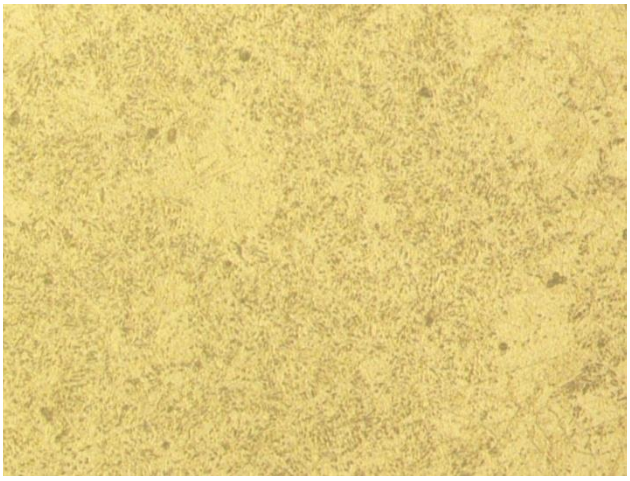

FIGURE 8: OPTICAL METALLOGRAPH OF 17-4PH (MAG.200X)

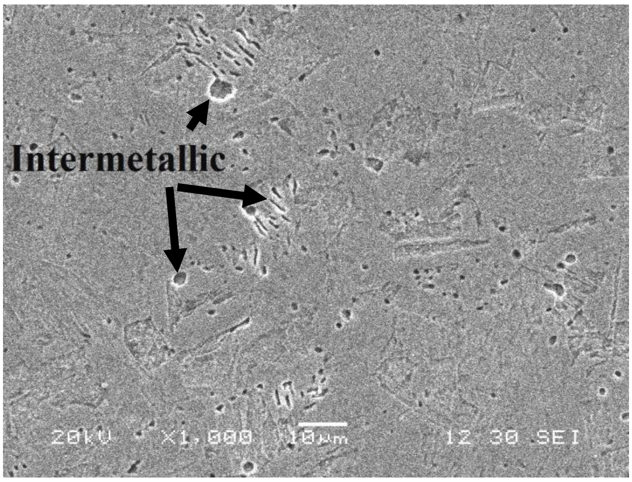

FIGURE 9: SEM IMAGE OF 17-4PH (MAG.1000X)

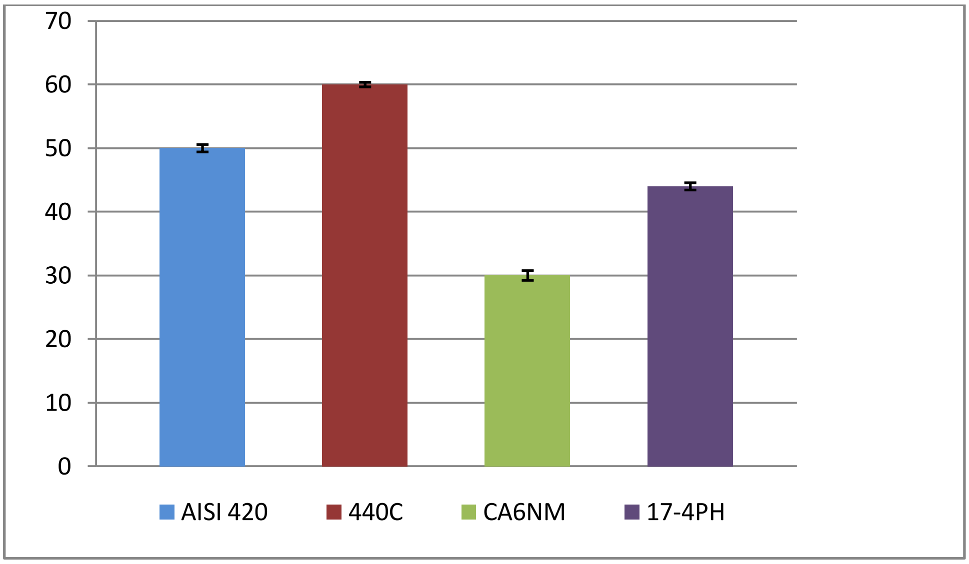

FIGURE 10: HARDNESS VALUES AFTER HEAT TREATMENT

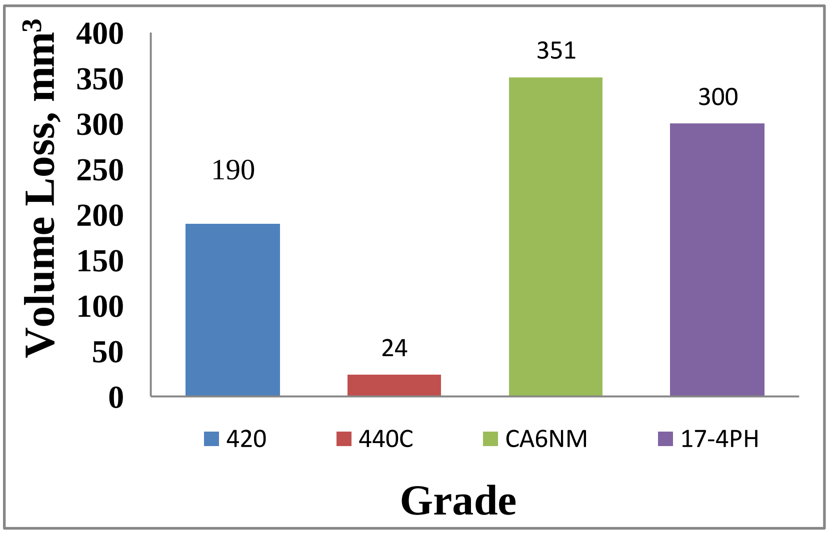

FIGURE 11: VOLUME LOSS OF TESTED GRADES

420	440C	CA6NM	17-4PH
			

FIGURE 12: ABRASION WEAR PATTERN ON TESTED SAMPLE

Tables

TABLE 1: CHEMICAL COMPOSITION ANALYSIS (wt %, BALANCE Fe)

Grade	C	Cr	Ni	Mn	Si	Mo	V	Cu	Cb
420	0.16	12.34	0.16	0.76	0.49	-	-	-	-
440C	1.03	17.43	0.10	0.45	0.24	0.40	0.13	-	-
CA6NM	0.10	11.88	4.30	0.71	0.54	0.83	-	-	-
17-4PH	0.01	15.81	4.48	0.72	0.26	-	-	3.01	0.02

TABLE 2: HEAT TREATMENT

Grade	Austenizing temperature, °C	Tempering/Aging temperature, °C
420	1040	150
440C	1050	150
CA6NM	980	600
17-4PH	1040	480

TABLE 3: RESULT OF EDS ANALYSIS OF AISI 440C

Element	Weight %
C	7.94
V	0.61
Cr	24.71
Mn	0.78
Si	0.19
Fe	65.05

TABLE 5: HARDNESS, DENSITY, WEIGHT LOSS AND VOLUME LOSS OF HEAT TREATED SAMPLES

Grade	Hardness, HRC	Density, g/cm^3	Weight loss, g	Volume loss, mm^3
420	50	7.72	1.4476	190
440C	60	7.61	0.1859	24
CA6NM	30	7.7	2.7063	351
17-4PH	44	7.78	2.3319	300