IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Mechanical Performance Evaluation Of Commercial Ultra-High-Strength Steels: Tensile, Impact, And Wear Behaviour

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Abstract

Ultra high Strength Steels (UHSS) are quenched and partitioned steels which are abrasion resistant and generally rely on a martensitic structure for better wear performance. However, in practice the steels are subjected to complex conditions where a combination of tensile, impact and wear properties ensures the tribiological performance. This work is the critical assessment of tensile, impact and wear behaviour and its correlation with microstructures and the phases present in commercially available ultra high strength steels.

1. INTRODUCTION

Ultra High Strength Steels (UHSS) are Steels which have Yield Strength greater than 780 MPa [1]. Quenched and partitioned (Q&P) steels yield an excellent balance of high tensile strength and good elongation [2-5]. During the quenching step, fully austenitized or intercritically annealed steels are quenched to temperatures to as below the martensite start (Ms) temperature, but above the martensite finish (Mf) temperature in order to form a controlled volume fraction of martensite. The quenched steels are then held at temperatures the same as or higher than the quench temperature during the subsequent partitioning step. Austenite that prevails after quenching is considered to be stabilized through carbon partitioning from martensite into austenite during the partitioning treatment [6].These type of steels are subjected to high impact and abrasive conditions like BF Top swivel chutes, chutes for ore conveyor ,lining for rotary mixers, Earth drills, Shear liners etc. The considered steels are mild carbon (0.15% 0.3%) and decent amount of alloying elements like Mn, Ni, Si,Mo and very low V and B in it .Thus due to these type of given carbon and concentration of alloying elements content there is occurrence of autotempering with various intensities of autotempering depending upon the carbon content with least carbon content having the maximum amount of autotempering [8].The amount of alloying element and occurrence of autotempering thus controlling the phases present and the prior austenite grain (PAG) size, lath and acicular structures thus affecting the tensile strength ,impact toughness ,wear behaviour of each grade of the commercialy available Ultra High Strength Steels[9]. The fraction of untempered martensite and presence of granular bainite and twinned martensite affects impact toughness values. The tensile strength generally has a direct correlation with tensile strength, both yield and the tensile strength meaning with increase in hardness the Y.S. and U.T.S values should increase [10].The amount of ferrite and retained austenite also plays pivotal role shaping the mechanical properties of steel particularly since both of them are softer phase and hence they are the controlling factor for elongation and tensile strength as well as toughness. Since autotempering as well as tempering leads to grain refinement which thus leads to decrease the effective grain size and thus decreasing the Ms temperature but is also a determining aspect of the tensile and toughness values [11].For wear behaviour of the concerned steels the grade having least impact toughness is expect to have high wear values, also grades having high hardness values are expected to have a better wear resistance [12].

But for Wear resistance of steels of hardness above 500VHN of steels is limited by work-hardening capacity, and fracture toughness. Increasing the base hardness perhaps reduces the ability to dissipate impact energy, and the depth of deformation also decreases. An ability to spread deformation to a greater depth can increase the wear resistance at a given hardness [12].

2. LITERATURE REVIEW

There is no standardization of commercially available ultra-high strength steels w.r.t chemical composition, mechanical properties etc. . With the increasing demand for ultra-high strength to withstand tensile, impact, wear various, there are various research going on to correlate microstructural ,tensile ,impact and wear behviour of the given grades to get a wider perspective for its usage at various location of abrasion resistance. At present, in Steel Industries, volume hardened liner plates are used in different plants for wear and impact resistant applications. Commercial ultra-high strength steel are assessed for their mechanical performance by standardized testing of tensile, impact toughness and wear resistance.

2.1 Tensile Properties

Tensile strength is the maximum stress that a material can withstand while being stretched or pulled before breaking or fracture. Tensile properties such as yield strength, ultimate tensile strength, elongation are done using with the help UTM (Universal Testing Machine). The main function of a UTM is to apply a controlled force to a test specimen and measure its responses to stress and strain. It provide critical data points which helps to maintain quality for research and development and provide quality product for industrial purpose. This evaluation ensures they meet the requirement for application in automotives, structural, and heavy machine industries where high strength-to-weight ratios and durability are critical.

Key Properties Measured

- Yield Strength (YS): The stress at which the material begins to plastically deform.
- Ultimate Tensile Strength (UTS): The maximum stress the material can withstand before breaking (Ultra -high strength steels shows UTS above 1300 MPa).
- Elongation: It is the measure of the material's ductility or how much it can deform before failure.
- Young's Modulus: It is the measure of stiffness of the material. It is also known as modulus of elasticity. It is numerically represented as: -

  Young's Modulus = stress / strain

2.2 Impact Behaviour

Impact testing measures the material's ability to resist sudden, high rate loading, which is very important for applications in heavy machinery parts , vehicle collision. Various types of notched-bar tests are used to determine the impact behaviour of the given material. This type of test will detect difference between materials which are not observed in tension test. Impact testing is done using Charpy and Izod test impact test. In Charpy impact test the Charpy specimen has a square cross section (10 x 10mm) and contains a 45 degree V notch with 2 mm deep notch of a 0.25 mm root radius. The specimen is supported as a beam in a horizontal position and loaded behind the notch by the impact of a heavy pendulum. While in Izod test the Izod specimen has a circular or square cross section specimen and contains a V notch near the clamped end. In Izod impact test the impact of loading is on the direction of the notch and the specimen is placed in vertical direction.

Key Properties Measured

- Impact Toughness/Energy: It is the ability of the material to absorb energy and resist fracture from sudden impact loading. It measures the ability of a material to absorb energy before it fracture and it is used for critical applications where materials may experience sudden shock load such from collision.

  The ordinary Charpy test measures the total energy absorbed in fracturing the specimen. It is measured by the given formula: -

$$E' = v_0 \left(\int_0^t P \, dt \right)$$

where v_0 = initial pendulum velocity

P = instantaneous load

t = time

However here the velocity of the pendulum is assumed to be constant.

2.2 Wear Behaviour

Wear behaviour refers to the loss of material from a solid surface due to relative motion and it is a important factor in material and component design as it can lead to performance degradation or failure. It is influenced by a combination of factors, including the materials involved, load, velocity, sliding distance, and environmental conditions, and it can occur through various mechanism like adhesion, abrasion, and fatigue. Different mechanism and conditions cause different wear rates and types of damage, such as scratching, pitting, or surface deformation. The standard wear test often involve specialized machine (e.g., impact abrasive wear machines) that simulate real-world conditions, but standard methods vary depending on the specific wear mechanism .

Key Properties Measured

- Wear Rate/Weight loss: The amount of material lost over time under specific wear conditions (e.g., abrasive, impact- abrasive).
- Hardness and Work Hardening: Wear resistance is highly correlated with the material's hardness, especially its ability to work harden on the surface under load.

3. Materials and Experimental Procedure:

The materials used in this experiment were Everhard 400 LE, Everhard 500 LE, Everhard C 550 & Hardox 500.The initial dimensions (length*breadth*height) of the plates were 300*150*12 mm. The samples are analysed in delivery (Quenched & Tempered) condition.

3.1 Materials Composition:

Table 1: Chemical composition of given plates (wt. %)

Sample	C	Mn	S	P	Ni	Si	Mo	C.E.V
Everhard-400 LE	0.13	1.160	0.006	0.009	0.016	0.37	0.140	0.372
Everhard-500 LE	0.26	0.760	0.007	0.010	0.019	0.265	0.150	0.487
Hardox - 500	0.26	0.700	0.007	0.010	0.057	0.26	0.025	0.530
Everhard- C 550	0.27	0.810	0.008	0.009	0.010	0.37	0.001	0.514

4. Sample Preparation

For microstructural analysis, samples were cut perpendicular to the weld using slow speed disc cutter. Microstructural analysis was carried out using, optical microscope (Leica, DMRX, Germany) and scanning electron microscope (Zeiss, SEM). These were hot-mounted in polymeric resin, ground and polished using silicon carbide emery paper to a fineness of 2000. Thereafter, cloth polishing using diamond paste of 6, 3 and 1 μm fineness was carried out. Etching was carried out using Nital solution (3 vol % nitric acid in ethanol).

- Hardox is the trade name for wear resistant plates of SSAB, Sweden whereas Everhard plates are manufactured by JFE Steel, Japan**.**

- Three plates Hardox-500, Everhard-400 LE and Everhard-500 LE of 12mm thickness were selected for comparative study. Equivalent Hardox-400 plate could not be made available**.**

5. Tensile Test (ASTM E8)

Tensile Test Specimen of as received plates of respective grades were prepared as per ASTM E8.The gauge length was 60 mm and the tensile test was performed using a Universal Testing Machine (UTM).Extension meter was used to determine the yield point of the specime

3(a)

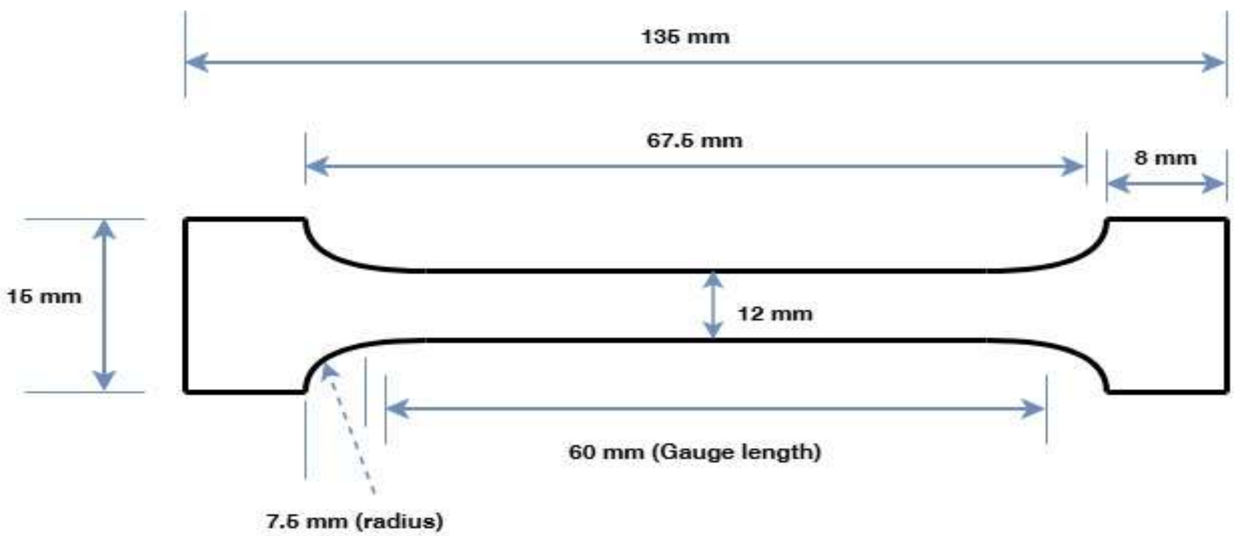

Fig 1. Schematic of the Tensile Test Specimen

5.1 Tension Test Procedure:

The tension test specimen shall be ruptured under tensile load. The tensile strength shall be computed by dividing the ultimate total load by the least cross sectional area of the specimen as calculated from actual measurements made before the load is applied.

UTS (Ultimate Tensile Strength) = Load/Area

5.2 Acceptance criteria for tension test:

In order to pass the tension test, the following are to be obeyed:

(a) The strain rate must be around 0.001/s during the test, since E8 test is quasi-static in nature.

(b) Crosshead speed must be controlled while determining the properties.

(c) Where gauge marks are used, the laboratory should employ documented gauge marking procedures to ensure that the marks and gauge lengths comply with the tolerances and guidelines of Test Method E8.

6. Impact Toughness Test (ASTM E23)

The impact toughness test of the specimens of given samples of respective grades by Charpy-V notch Impact Toughness Test as per the norms of ASTM E23 test method

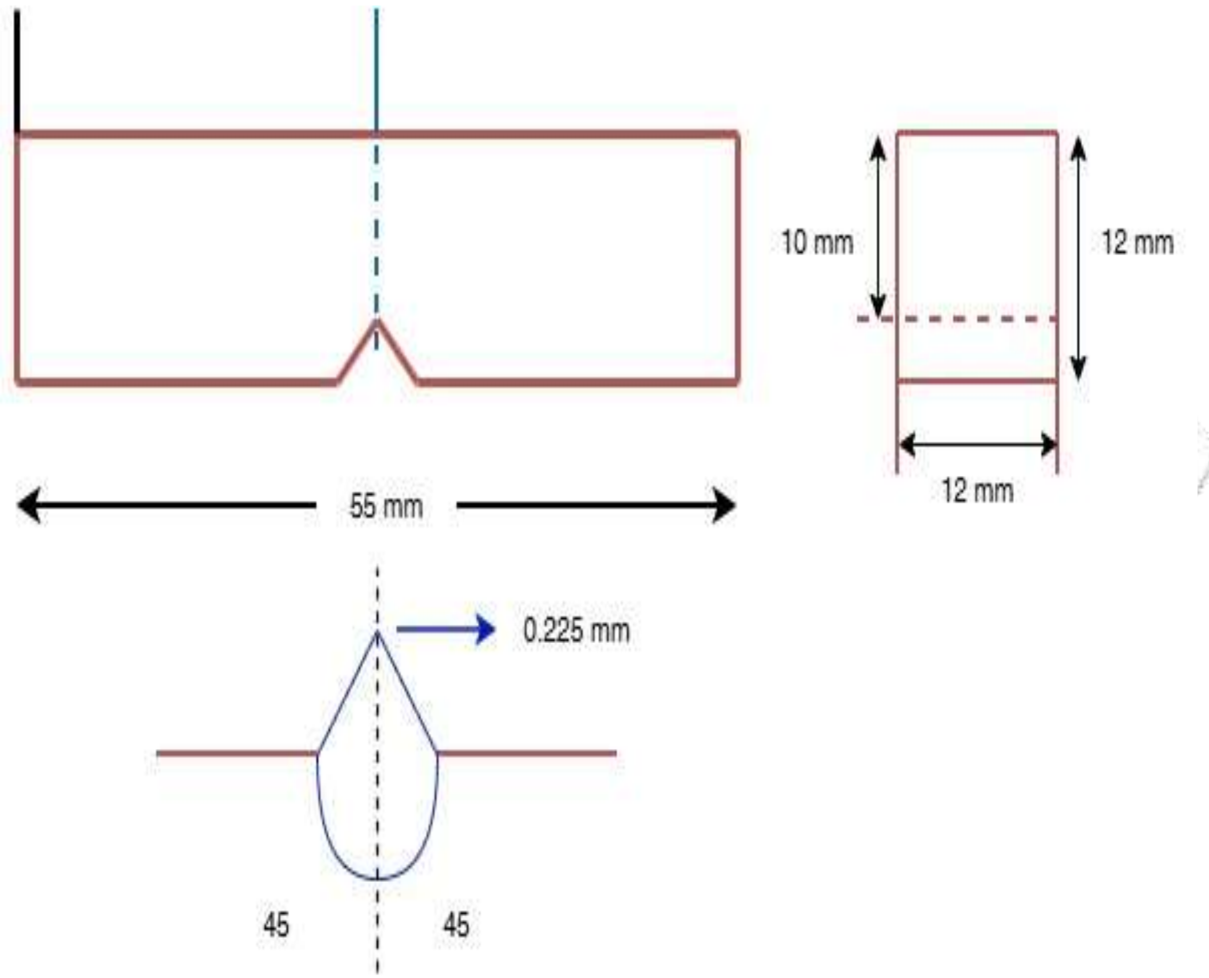

Fig 2. Schematic of the Charpy V-notch Impact Test Specimen

6.1 Charpy Test Procedure:

- Calibrate the machine: The pendulum is lifted to its starting position and released it without a specimen and check that the drag-indicate returns to zero, which confirms the machine is properly calibrated.

- Specimen Preparation: Use a standardized specimen with a V-notch. Place it horizontally on the machine's support, with the notch facing the direction of the hammer' strike.
- Release the pendulum: The drag indicator is reset and the pendulum is released. The hammer will swing down and strike the specimen, fracturing it.
- Measure energy absorption: The energy absorbed by the specimen prevents the pendulum from reaching its original height. The difference in height is recorded to calculate the energy absorbed, which is recorded on a dial gauge.

The ordinary Charpy test measures the total energy absorbed in fracturing the specimen. It is measured by the given formula: -

$$E' = v_0 \left(\int_0^t P \, dt \right)$$

where v_0 = initial pendulum velocity

P = instantaneous load

t = time

However here the velocity of the pendulum is assumed to be constant.

7. Two Body Wear Test /Pin on Disk Test (ASTM G99):

The two body wear test i.e., the pin on disk test was performed as per ASTM G99 norms on DUCOM Tribometer and the corresponding Wear vs. Temperature plot and the Coefficient of Friction vs. Time was plotted with the help of Winducom Software of the same company DUCOM, New York,USA.

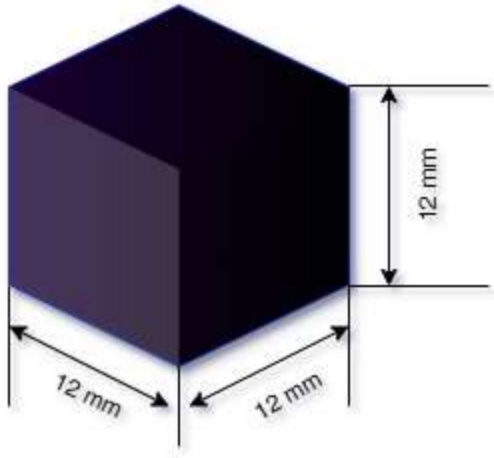

Fig 3. Schematic of Pin-on-Disc wear test

8. Results and Discussion

8.1 MICROSTRUCTURAL ANALYSIS

The sample specimens of respective grades were analysed through thickness centre quarter and top and one best representative of each grade is shown below:

(i) Everhard 400:

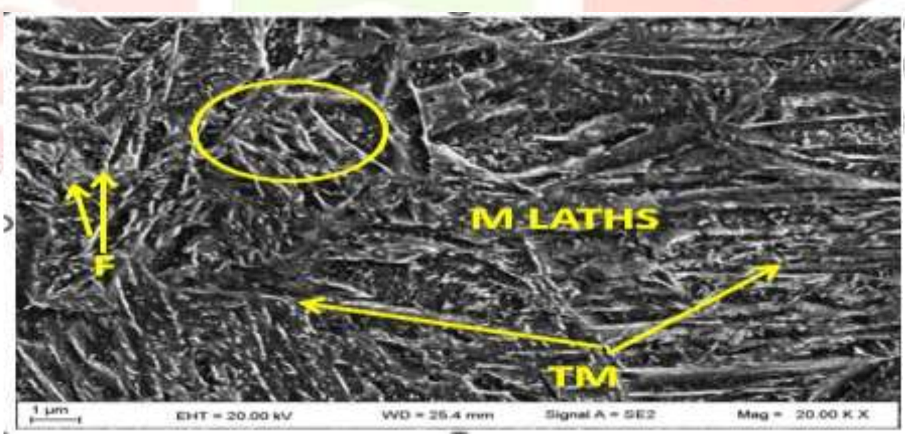

Fig 4. SEM Micrographs showing the microstructure of Everhard 400. The symbols M, TM, F,represents Martensite, Tempered martensite & Ferrite respecrtively.

(ii) Everhard 500:

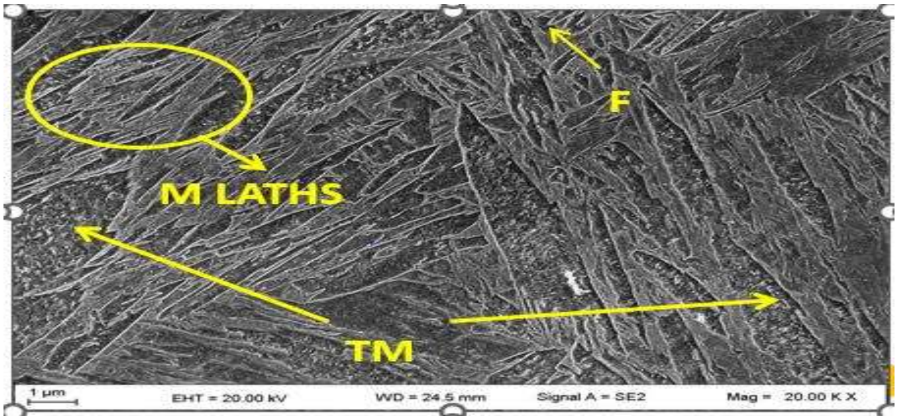

Fig 5. SEM Micrographs showing the microstructure of Everhard 500. The symbols M, TM, F represents Martensite, Tempered martensite, & Ferrite respectively.

(iii) Hardox 500:

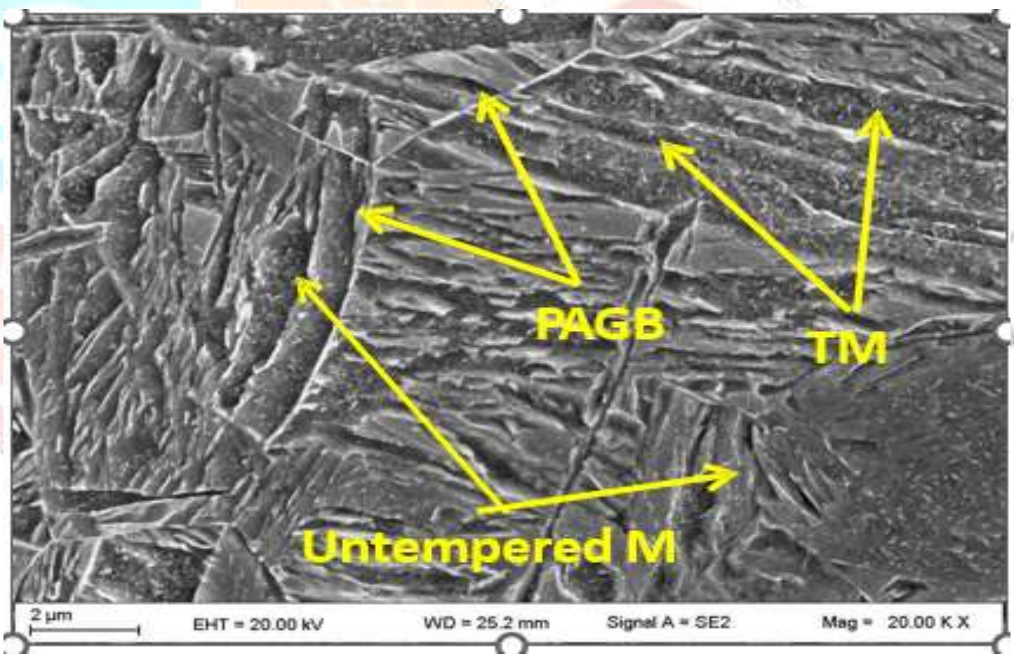

Fig 6. SEM Micrographs showing the microstructure of Hardox 500 .The symbols M, TM, UTM, GB, F, PAGB represents Martensite, Tempered martensite, Untempered martensite, Granular Bainite, Ferrite & Prior-austenite grain boundaries respectively.

The samples analysed were Everhard 500,Hardox 500 & Everhard 400 all of the representative images are displayed at 20,000 X and the microstructural analysis of the given samples shows that Tempering has occurred most in Everhard 400 then Everhard 500 and least in Hardox 500.Also, the amount of umtempered martensite was most found in Hardox 500 as well as Hardox 500 may contain some granular bainite.

9. Tensile Test

The tensile test for the respective grades was conducted and the results obtained after the tests are depicted in the graphs separately for YS, UTS & Elongation.

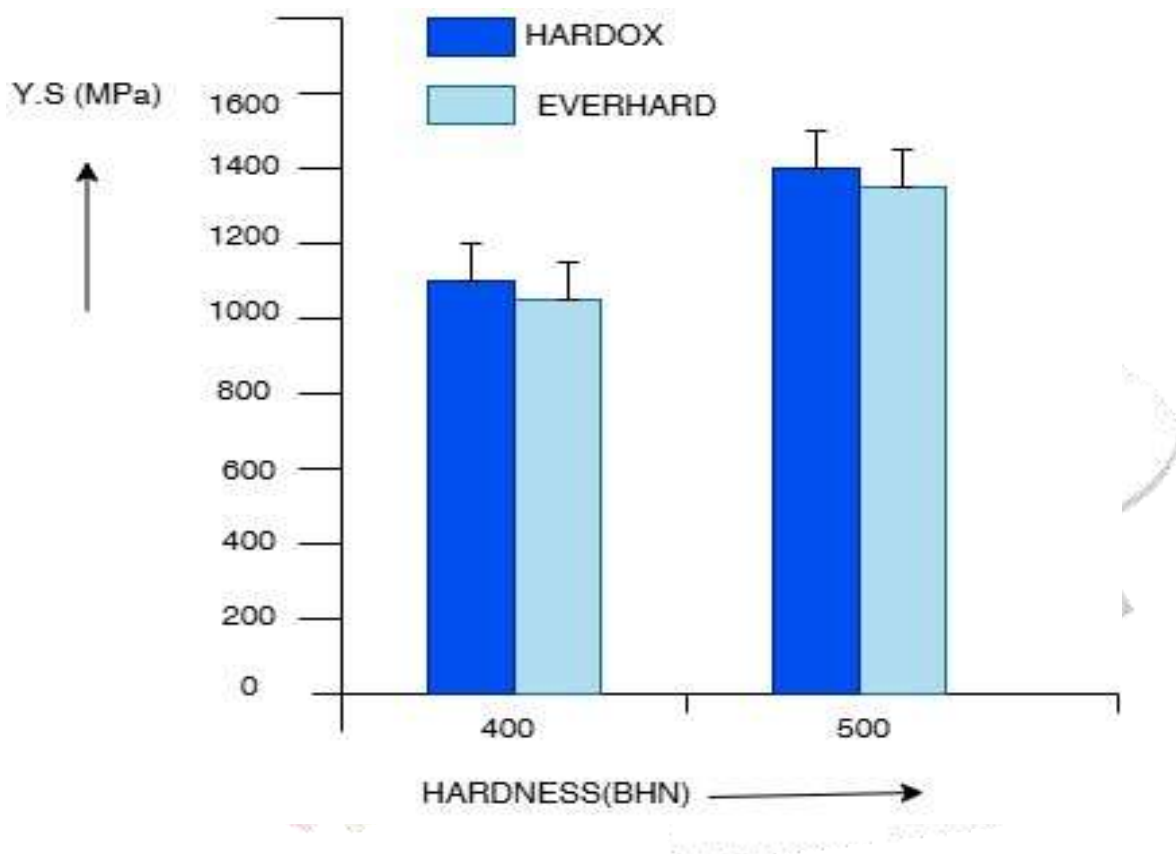

Fig 6.Yield Strength (MPa) vs. Hardness (BHN) For Hardox 400, Hardox 500 &Everhard 400 & Everhard 500.

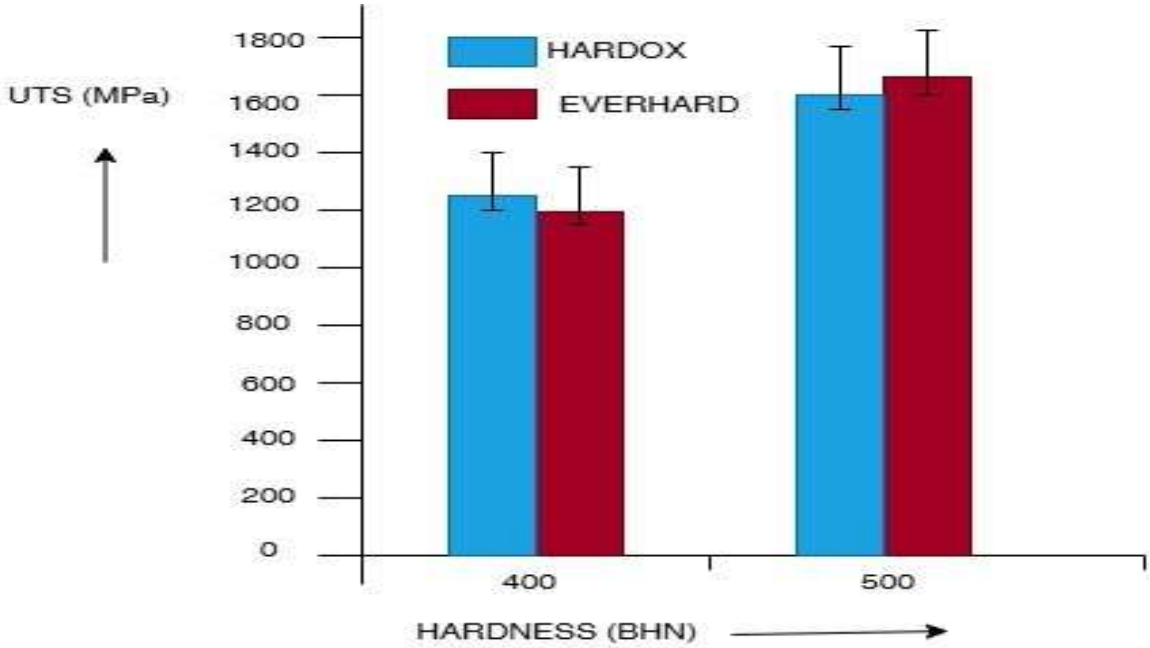

Fig 7.Tensile Strength (MPa) vs. Hardness (BHN) For Hardox 400, Hardox 500 &Everhard 400 & Everhard 500.

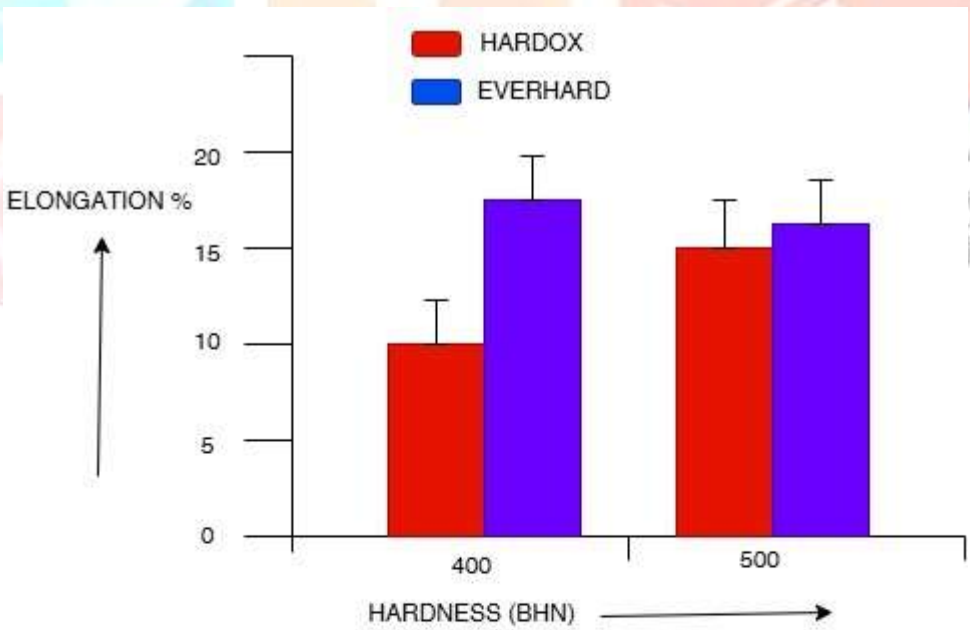

Fig 8.Elongation (%) vs. Hardness (BHN) For Hardox 400, Hardox 500 &Everhard 400 & Everhard 500

The results of the tensile test for Hardox 400 was taken from literature to compare to its contemporary Everhard 400 [14] .While for Everhard 500,Hardox 500,Everhard 400 tests were performed. The tensile properties have a dependence on Effect of autotempering, Presence of softer phase like Ferrite ,presence of Untempered Martensite and Prior Austenite Grain size(PAG). The factors listed manifest the values of each tensile properties for which graphs are plotted.

10. Impact Toughness Test

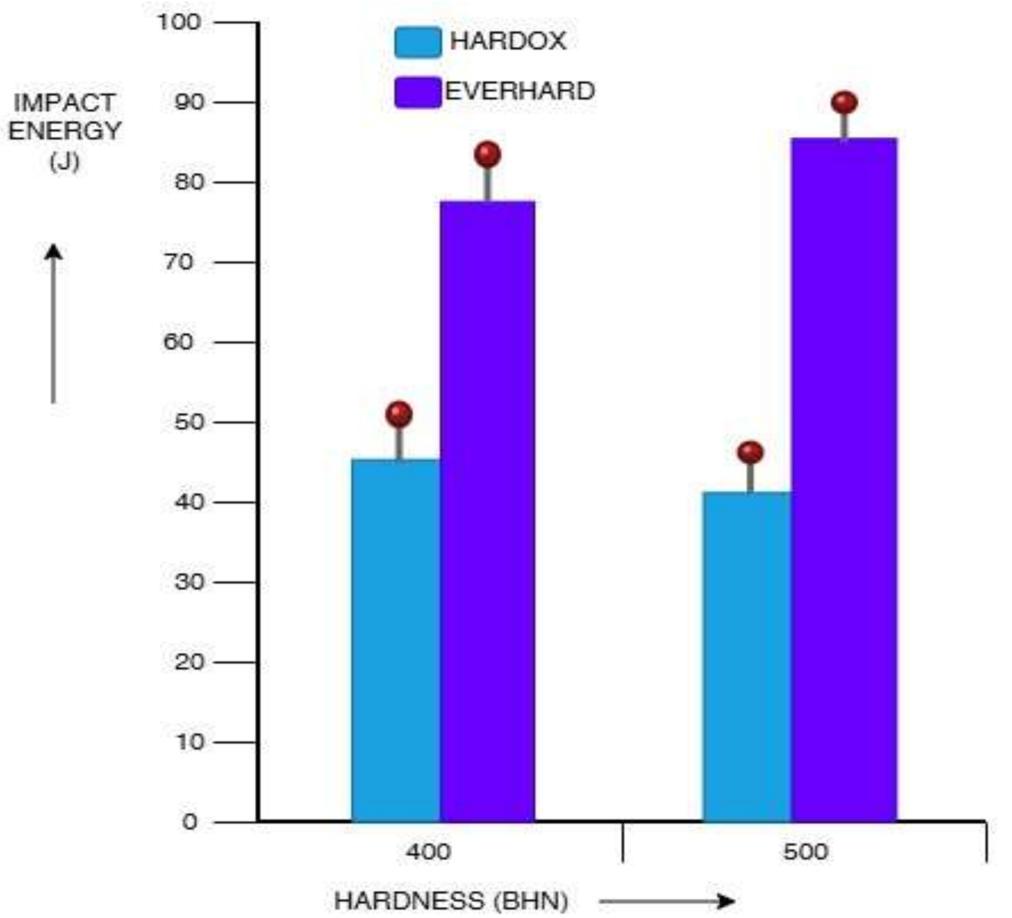

Fig 9 . Impact Energy (J) vs. Hardness (BHN) For Hardox 400, Hardox 500 &Everhard 400 & Everhard 500

The result obtained for respective grades are depicted in the impact energy vs. Hardness plot. These plots show Everhard performs better over Hardox in terms Impact energy absorbed probably due to autotempering due to higher Ms temperature imparting them the respective prior austenite grain size(PAG) and presence of untempered martensite are detrimental factors imparting them the impact energy values depicted.

11. Wear Test

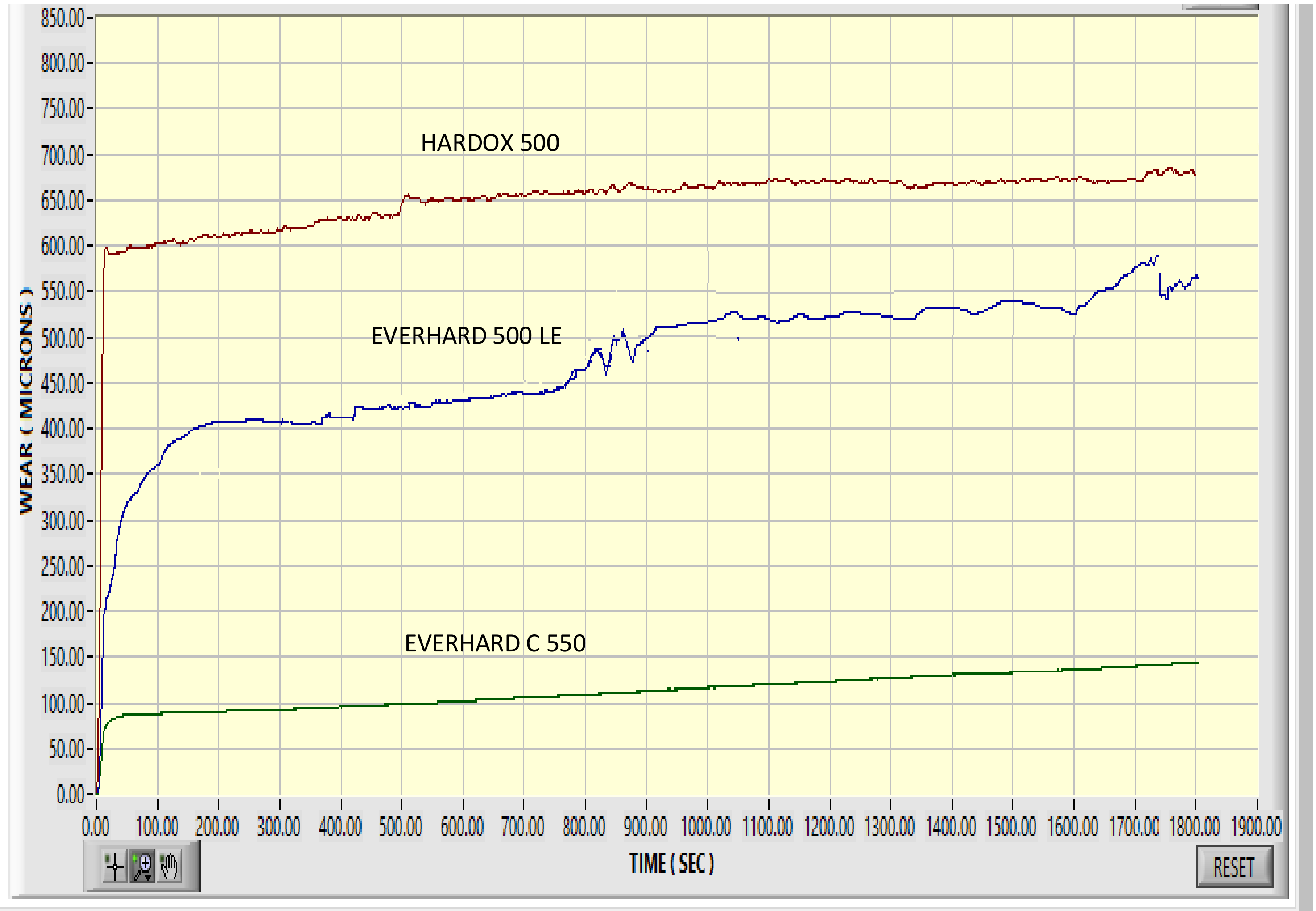

Fig 10. Wear (Microns) vs. Time (sec) plot for Everhard 500LE, Everhard C550, Hardox 500

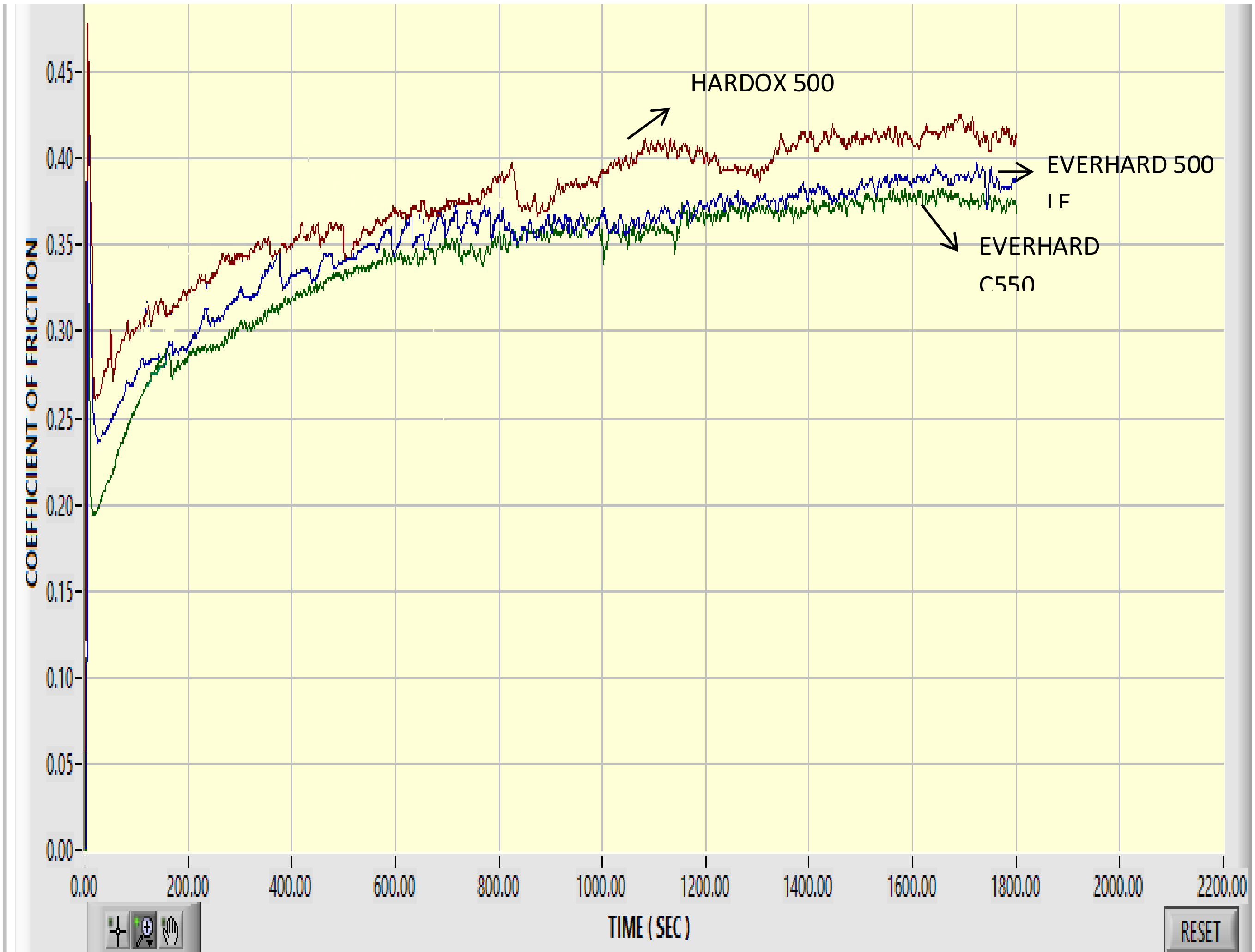

Fig 11. Coefficient of Friction vs. Time (sec) plot for Everhard 500LE, Everhard C550, Hardox 500.

The following plots were obtained by Winducom software of Ducom Tribometer when the wear tests were being performed simultaneously at 300 rpm speed and track diameter 100mm,also the time duration being 30 minutes. The wear tests showed that the Everhard C550 is maximum wear resistant ,Everhard 500 being in middle while Hardox 500 was least and correspondingly coefficient of friction vs. time plots observation is denoted. However wear has a inverse relation with impact toughness while coefficient of friction has dependency on none of them.

12. CONCLUSIONS

1. Everhard 500 and Everhard 400 plates were having equivalent tensile properties to Hardox 400 and Hardox 500 plates respectively.

2. Everhard plates showed superior impact toughness compared to Hardox plates, which makes them suitable for higher impact applications such as chutes with lump material falling from high height.

3. A higher toughness is attributed to microstructural features such as higher extent of tempering possibly due to its higher Ms temperature facilitating greater extent of auto- tempering. However, other factors like PAGS (Prior-austenite grain size), Vol% of granular bainite, twinned martensite etc. also need to be looked at.

4. In nutshell, Everhard plates can substitute equivalent hardox plates and additionally, these have superior weldability and impact toughness properties.

5. Everhard C550 is the maximum wear resistant, Everhard 500 LE being in the mid-ranged and Hardox 500 being the least.

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