EFFECT OF CRYOGENIC TREATMENT ON THE PERFORMANCE OF STRAW COMBINE BLADE

BY

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CERTIFICATE – I

This is to certify that this thesis entitled **“Effect of cryogenic treatment on the performance of straw combine blade”** submitted for the degree of **Master of Technology** in the subject of **Farm Machinery and Power Engineering** to the **Chaudhary Charan Singh Haryana Agricultural University, Hisar** is a bonafide research work carried out by **Chander Jakhar (2019AE01M)** under my supervision and that no part of this dissertation has been submitted for any other degree. The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE – II

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVATIONS

%	:	Per cent
°	:	Degree
ANOVA	:	Analysis of variance
cm	:	Centimeter
d.f.	:	Degree of freedom
S.S.	:	Sum of squares
g	:	Gram
Fig.	:	Figure
h	:	Hours
ha	:	Hectare
rpm	:	Revolution per minute
F	:	Coefficient of friction
N	:	Newton
S	:	Sliding distance
V	:	Velocity
r	:	Radius
i.e	:	That is
Kg	:	Kilogram
kgf	:	Kilogram force
km	:	Kilometer
m	:	Meter
mm	:	Millimeter
Rs.	:	Rupees
S	:	Second
SEM	:	Scanning electron microscope
EDS	:	Energy Dispersive Spectroscopy
CRD	:	Cathode ray deflection
yr	:	Year

CHAPTER-I

INTRODUCTION

The mechanization of harvesting operation is essential to minimize the cost of harvesting, grain production cost, grain loss, turnaround time, weather risk, and to increase benefit by appropriate technology. At present, developed countries all over the world are using automatic combine harvester for harvesting grain and straw combines for threshing the stalks left behind after harvesting of wheat crops. Straw combine recovers wheat straw which can be used as cattle feed. The harvesting machinery (combines, reapers and straw combines) is developed not only to overcome the shortage of labor and timely operations but also to facilitate the multi cropping sequence in India. Due to recovery of wheat and rice straw by straw reaper there is reduction of environment pollution.

The cutting and chopping blades of straw combine is generally made up of high carbon steel. These high carbon steel blades contain 0.60 to 1.00 % carbon with manganese contents ranging from 0.30 to 0.90 % (Chahar *et al*. 2009). The increase of carbon as the primary constituent of alloy for higher strength and hardness of steels. It is usually the most economical approach to improve the performance. Therefore to increase the performance of steels in cutting applications, it is common to raise the carbon content to the highest practical level. However, during cutting at high temperature and in abrasive environment, these cutting materials faces excessive surface degradation which ultimately reduces the life of the blade and increases cutting cost of the machine. In recent times, the cryogenic treatment has emerged as popular surface treatment method for improving the surface properties of materials.

Cryogenic treatment is the process of cooling a material to temperatures far below room temperature (-80°C to -196°C), but when the treatment is applied between temperature (-140°C to -196°C) is termed as deep cryogenic treatment and when applied between temperature (-80°C to -140°C) is termed as shallow cryogenic treatment (Thornton *et. al*., 2014). Basically “Cryogenic” word is taken from the two Greek words - cryo means freezing and genic means to produce. Heat treatments applied at very low temperatures is referred to as cryogenic. The cryogenic treatment process can produce harder, more wear-resistant materials with many other beneficial properties. In case of steels to achieve better structure and to get most desired properties, it is recommended by the most researchers to execute deep cryogenic treatment (DCT). The cryogenic treatment is carried out in the presence of some coolant like liquid nitrogen and helium. Liquid nitrogen is mainly used as coolant because of its extremely low boiling temperature (-196°C), low cost and ready availability (Reitz and

Pendray 2001). During cryogenic treatments, samples are cooled gradually by means of a control unit using coolant to get the required cryogenic temperature. After a waiting period, the samples are gradually brought back up to room temperature. Owing to the cryogenic treatment applied to cutting tools, improvements in such tool features as abrasion resistance, hardness, toughness, and electrical conductivity are ensured by the constriction resulting from cooling and the subsequent homogeneity of the carbide distribution. Over the years, a number of researchers have worked on the performance evaluation of the materials after cryogenic treatment. Akincioglu *et. al*., 2015 concluded that life of cutting tool increased by 27 % and the main cutting wear decreased by 11% with deep cryogenic treatment. Gill *et. al*., 2011 conducted experiment on flank wear and machining performance of cryogenically treated tungsten carbide inserts concluded that the cutting life of tungsten carbide inserts increased by 27 % in case of shallow cryogenic treatment and 37 % in case of deep cryogenic treatment. Similarly, Singh *et. al*., 2020 studied the abrasive wear behavior of cryogenically treated boron steel used for rotavator blades concluded that hardness of cryo-treated specimen improved by 260.73 % and abrasive wear reduced by 60 % as compared to untreated material. Marian *et. al*., 2017 conducted experiment for determination of the wear resistance of devices used for cutting the stalks of agricultural plants and concluded that the weight loss of blades due to wear was maximum at the centre of the blade. In combine, due to wear, the middle knife has a weight loss of 1.9654 g representing 2.498 %, after 100 hours of operation. Akincioglu *et al.*, 2015 concluded that as a result of cryogenic treatment, cutting forces decreased and surface roughness improved in parallel with improvements in the wear resistance of cutting tools. Unlike conventional heat treatment, cryogenic treatment is not a superficial method, it affects the entire material. It enhances the toughness and hardness values of cutting tools like in carbide tools by homogenizing the carbide distribution within them. In order to achieve maximum benefits from cryogenic treatment on cutting tools, the cryogenic treatment parameters (holding temperature, holding time, identification of heat treatment to be applied, cooling rate *etc*.) should be applied under optimum conditions according to the tool materials and operational settings *i.e*. in deep cryogenic treatment the holding time is generally taken as 12-24 h.

Arslan *et. Al.,* 2011 and Vidyarthi *et. al*., 2013 studied on improving the properties of steels by deep cryogenic treatment. They noted interesting positive effects in tool steels, carburized steels, cast iron and other materials. However, the mechanisms behind this treatment remain unclear, making it difficult to predict the effects of this treatment on a particular alloy. Most researchers believed that at the end of the heat treatment, a low percentage of austenite is retained at room temperature. The retained austenite, as a soft phase in steels, can reduce the product life. Now deep cryogenic treatment changes the austenite into martensite which increases the life of cutting tool, but in case of high carbon steel the life of cutting tools increased due to the precipitation of secondary fine carbides. Therefore, we can see the cryogenic treatments contribute to the enhancement of the wear resistance and the increase in hardness is mainly through the precipitation of fine secondary carbides and the transformation of retained austenite into martensite. Thus, specific experimental testing is required for each material to be treated.

After review over drawbacks of high carbon steels (HCS) and the benefits of deep cryogenic treatment (DCT) on work piece, a study was conducted on high carbon steel work piece with cryogenic treatment with the following objectives:

1. To carry out wear analysis of cryogenic coated and uncoated straw combine blades.
2. To study economic feasibility of cryogenic coated blades.

CHAPTER-II

REVIEW OF LETRATURE

This chapter deals with the relevant research carried out by various investigators. It provides guidelines for the framework of the study. Here we compare the various results taken out through various methods by different investigators. The available information on the subject is presented under headings:

2.1 Blades materials and wear analysis

2.2 Studies related to cryogenic treatment

2.1 Blades materials and wear analysis

Lau *et al*. (2000) studied wear characteristics and mechanisms of a thin edge cutting blade. The shape and the size of the thin blade cutters used in these experiments were made according to China standard GB1211-86 similar to ISO563-1981 and two types of blades AISI steels 1045 (0.42±0.50% C, 0.60±0.90% Mn, 0.04% P, 0.5% S, 0.15±0.30% Si) and 1090 (0.85± 0.98% C, 0.60±0.90% Mn, 0.04% P, 0.05% S) was used. Both steel specimens were hardened by induction heating and tempered to form various structures. The wear tests were carried out on a self-made simulating ensilage-cutting machine. The relative cutting speed between the fixed and moving cutters was kept at 20.66 m s^{-1}, while the cutting period varied from 5 to 360 min. From the results it was concluded that the wear characteristics of thin edge cutting blade will be highly affected by their geometry and the thickness of the blade. The wear rates increased with time abruptly at the initial stages mainly because of surface fatigue abrasion but with the increase in cutting duration, the wear rate decreased gradually because the blade edge thickness increased.

Jha *et al*. (2003) carried out a study on correlating micro structural features and mechanical properties with abrasion resistance of a high strength low alloy steel. They studied the wear behaviour, microstructure, tensile properties and hardness, for this the steel was subjected to various heat treatment for improvement in microstructructural features and wear properties. The results of this study concluded that apart from hardness the ductilty of steels also have important role in deciding the wear characteristics. An optimum level of hardness only leads to the best wear performance of the steel. If lower than the optimum level of hardness then there will be higher wear rate due to over softening of the samples and if higher than the optimum level, causes inderior wear performance due to brittle fragmentation of the material. Presence of martensite increases the hardness of the specimen significantly but at the same time it tends to embrittle the smaple when present in large quantites and this leads to higher wear rates. The study also concluded that predominance of either of the mechanisms adversely affects the wear rate.

Chang (2005) studied the rolling or sliding wear performance of four different carbide-free high silicon bainitic steels of different chemical compositions with detailed microstructural characterization. Hardness tests were carried out using a standard vickers diamond pyramid hardness testing machine. Microscopy was performed both with a scanning electron microscope and olympus optical microscope. The amount of retained austenite was determined using X-ray diffraction. The results indicated that harder materials exhibited lower wear rates and the presences of inclusions and allotriomorphic ferrite in the microstructures were detrimental to the wear performance. The excellent properties of the experimental alloys are attributed to the absence of carbides, the ability of the microstructures to tolerate a large degree of plastic strain and the mechanically due to martensitic transformation of retained austenite.

Bayhan (2006) conducted a study on wear reduction of chisel plough share made of low alloy steel via hard facing. The chemical composition of chisel plough shares used in the study was C 0.3196, Si 0.3965, S 0.0297, P 0.0141, Mn 1.2073. The surfaces is designated as EH-600, EH-350 and EH-14 Mn which have 50 HRC, 35 HRC and 3 HRC cutting edge hardness values, respectively. The chisel plough share was coated with three different hard facings. The plough was operated for 10 km in the field and the plough share was cleaned and weighed on a scale with ± 0.01g sensitivity in order to measure the amount to wear rate. The wear of hard faced edge share was slightly less as compared to regular share mainly because of hardness. The wear rate was related to both hardness and chemical composition of the materials. The carbon and manganese proportions have maximum effective on the wear rate.

Bejar and Moreno (2006) studied the abrasive wear resistance of boronized 1020, 1045, 4140 and 4340 steels in a mixture of dried borax and SiC at temperatures of 1223, 1273 and 1323 K, for 2, 4 and 8 h, respectively. Flat samples with a 25 mm diameter and a thickness of 5 mm were prepared from the steels. It was observed that the samples boronized at 1223 K presented a relatively high mass loss which can be attributed to the fact that at such temperature the boride layers were relatively thin. Therefore, the boride layer thickness increases with temperature.

Karoonboonyanan *et al*. (2007) compared wear analysis of two thermally sprayed (HOVF- sprayed WC/Co and plasma-sprayed Al2O3-Tio2/NiAl) rotary tiller blades made from carbon steel with a nominal composition of Fe – 0.5, C – 0.9, Mn – 0.7Si (wt.%). The test was conducted on an area of 3.2 ha on sugarcane field after harvesting. The wear rates of WC/Co-coated blades were significantly lower than the uncoated blades as compared to Al2O3 coated blades. In WC/Co thermal spray coating the coated blades showed a great improvement in the wear protection.

Horvat *et al.* (2008) conducted the study on reduction of mould board plough share wear by combination technique of hardfacing. They compared regular mould board plough shares and two hardfaced mould board shares made of different basic materials, steel EN 10027 and EN 50Mn7. These shares were hardfaced by a combination of two welding processes, namely shielded metal arc welding and high frequency induction welding. The wear was determined by measurements of the changes of dimensions and weight losses during ploughing. The dimensions and weight losses were lower for both types of hardfaced plough shares in comparison to regular mould board shares. The hardfaced plough shares also resulted in lower fuel consumption, lower production cost and higher rate of work. The results of the study showed that this method can be recommended as an efficient solution for plough share wear protection.

Chahar *et al.* (2009) carried out study on wear characteristics of reversible shovels of tractor mounted cultivator. They selected four shovels having 0.41, 0.50, 0.59 and 0.65 % carbon content for the study. The moisture of abrasive sand used was 10-15 %. The study revealed that the shovel with maximum carbon content wore out minimum at each interval. The wear was measured with respect to width and thickness of shovels. The maximum wear loss occurred at the tip of the shovel. The wear loss in shovel decreased by 37.44 % with increase in carbon content from 0.41 to 0.65 %. The change in length and width of shovels were negligible as compared to their thickness. They concluded that the shovel with higher carbon content have higher tolerance power to wear.

Singh *et al.* (2010) carried out study on low stress abrasive wear response of boron steel under three body abrasion with various heat treatments (annealing, inter critical annealing, quenching and tempering) and shot peening intensities. The wear rate of inter critical annealed and quenched and tempered steels were considerable less than annealed steels. The wear rate was reduced significantly irrespective of heat treatment schedule at the critical peening intensity of 0.27 mm. The shot peening intensity varied in the range 0.17 to 0.47 mm.

Kaur *et al.* (2011) conducted a study to know the wear performance of four different materials of rotary blades mainly T1 (Low carbon steel), T2 (Low alloy steel), T3 (High carbon spring steel) and T4 (Low carbon steel). The blades were operated for 150 h in loamy and sandy loam soils. The performance of blades were notes on the basis if weight losses and width losses in percentage. They concluded that maximum average weight loss was 6.76 % in T2 blade having 0.28 % carbon content and minimum 0.86 % in T3 blade having 0.64 % carbon content in loamy soils. In sandy loam soils, maximum average weight loss was 10.02 % that occurred in blade T4 having carbon content of 0.25 % and minimum was 4.09 % in blade T3 having 0.64 % carbon content. They observed that width of worn out blades decreased with operational hours. The maximum and minimum average loss in width was

13.20 and 3.18 % in blade T2 and T3 in loamy soils, whereas, it was 14.68 and 8.27 % in blade T4 and T3 in sandy loam soils.

Singh and Saxena (2011) conducted study for characterization of materials used for rotavator blades. The blades were heat treated differently (quenching and tempering in steels and austempering in boron steels) in order to achieve varying microstructures. The two boron containing steels (50B50 and 30 MnCrB4), plain carbon steel (EN-45) and low alloy high carbon strength steel (SAE-6150) were considered under study. The study showed the formation of tempered martensitic structure with fine laths, which increased the mechanical properties like hardness, tensile strength and percentage elongation (8-12 %) in case of boron steels and similarly in high strength low alloy steel. This study also revealed that carbon was most influencing element of steel and varied from 0.3 to 0.53 %. The wear rate of rotavator blades were found in order EN-45 (QT) 30MnCrB4 (Au) > 50B50 (Au) > 30MnCrB4 (QT)) > SAE-6150(QT > 50B50 (QT). The wear rate of EN-45 (QT) was highest because of presence of low alloying elements and lowest in 50B50 (QT) steel as boron improved harden ability and fine micro-structure in the steel during quenching and tempering.

Nalbant and Palali (2011) studied the effects of different material coatings on the wear of plowshares used in soil tillage. The plow shares were coated with 20 µm hard chromium by electrolysis method, 20 µm electro less nickel by chemical treatments and 4 µm titanium nitride by physical vapour deposition to increase wear resistance and compared with uncoated plowshare. The coated and uncoated plowshares were mounted on test equipment to analyze their wearing characteristics in soil at speed of 5.8 km h^{-1}. The thickness of the coating and the mass loss of the plowshares were measured each 1.18 km upto 10.8 km. The wear values for the coated and uncoated plows were in a close range for the tillage length of 10 km in the soil. The results showed that the wear length of the electroless nickel coated specimen was higher than the others. However the titanium nitride coatings had a higher wearing resistance than the hard chromium and electrolysis nickel coatings.

Kang *et al*. (2012) carried out a study on wear behavior of thermal spray coatings on rotavator blades made of high tensile steel (EN-14B). They compared three different thermal coated blades (WC-Co-Cr: 86WC/10Co/4Cr, cr3c2NiCr:75Cr3/25NiCr, stellite-21) with one uncoated blades. The rotavator was operated in 50 acres full of stubbles. The wear was measured by weighing each blade to determine the weight loss. They observed that the Stellite-21 coated blade showed some wear damage, Cr3C2NiCr coated blade showed very little wear damage and WC-Co-Cr coated blade showed almost negligible wear damage. They concluded that WC-Co-Cr coated blade display a much higher wear resistance than the other coated blades as well as the uncoated blades.

Abbas and Alwan (2014) studied the effect of quenching media on the mechanical properties and abrasive wear resistance of steel blade (34Cr4). The hardness of blades increased with varying quenching media. The wear resistance increased because of martensitic and retained austenite which was formed in steel as a function of quenching media and the increase in abrasive wear resistance of the samples were due to formation of carbide and decrease toughness with varying quenching media. They concluded that the wear resistance increased with decreasing toughness to values 48.3, 45.0, 40.2 and 27.0J. The damage on the worn decreased due to effect of heat treatment (high hardness). They also concluded that wear resistance depends upon hardness, toughness and mechanical properties of the steel blade.

Bialobrzeska and kostencki (2015) compared the abrasive wear characteristics of low-alloy boron steels plowshares in both laboratory (dry sand-rubber wheel abrasion test) and field conditions. The wear behavior of these steels has been investigated using Russian standard T-07 wear test equipment in which the steel samples were worn by coarse alumina particles (grit size #90). The wear of the steels was evaluated by weight loss and their wear mechanisms were investigated using scanning electron microscopy. The obtained results of laboratory and field tests showed that hardness seems to have a secondary role in controlling the wear rate. The abrasive wear rate depends strongly on the predominant mechanism of wear, which in turn is strongly dependent on the microstructure. The steel with the highest carbon content indicated the lowest values of all roughness parameters measured after field and laboratory tests.

Rementeria *et al*. (2015) carried out study on reciprocating-sliding wear behavior of nanostructured and ultra-fine high-silicon bainitic steels. The chemical compositions of the alloys investigated are 0.30C-1.48Si-2.06Mn-0.43Cr-0.27Mo, and 0.99C-2.47Si-0.74Mn-0.12Ni-0.97Cr-0.03Mo-0.17Cu wt. %, encoded as 0.3C and 1.0C, respectively. Heat treatments were performed in the furnace (Adamel Lhomargy LK02) and microstructures were examined by optical microscopy and field emission gun-scanning electron microscopy. The results concluded that the wear resistance of high-carbon high-silicon bainitic steels was at least twice superior to that of medium-carbon high-silicon bainitic steels with similar hardness values. The highly refined microstructure and the transformation under strain of the austenite films, contributes to the surface hardening and improve the wear performance.

Punamchand *et al*. (2016) studied influence of surface hardening process on wear characteristics of soil working tools. They concluded that surface modification techniques like electric deposition, shot peening, hard facing, diffusion coating, vapor deposition and thermal spraying are very beneficial for wear resistance. The material hardness, moisture content, abrasive particle size, length of abrasive path, speed and normal load applied also played important role on abrasive wear of working materials.

Balos *et al*. (2016) studied the abrasive wear behavior of ADI materials (ferrite and pearlitic ductile iron) with various retained austenite content. The Samples were sustempered at different temperatures *i.e*. 300°C, 350°C and 400°C. Grit paper abrasive grain size (P 240, P 500, P 800) and different wear loads (0.5 kg, 1.3 kg, 2 kg) were the two parameters which were varied stress-assisted phase transformation of retained austenite into martensite phenomenon. The hardness of ADI materials were found to play major roles in wear behaviour. Presence of metastable, low carbon - enriched retained austenite were another important factor in the occurrence of phase transformation of retained austenite into martensite phenomenon.

Rana (2017) compared wear characteristics of ADI (Austempered Ductile Iron) rotavator blades (3) with other indigenous (1) and imported (1) rotavator blades. The material composition was determined by using Scanning Electron Microscope (SEM). The wear of rotavator blades were measured gravimetrically as well as dimensionally. In gravimetric wear study weight of all blades were taken on an electronic balance after each 25 h of working operation. The dimensional wear was measured with respect to width and thickness at different section of the blades. The test result showed that average gravimetric wear rate of ADI and indigenous blades were 110.08, 129.98, 154.42 and 106.87 % of imported blade. The average width wear rate of ADI blades (T1), (T2) and (T3) at starting, bent and leg section were (0.36, 025 and 0.025 mm h^{-1}), (0.40, 0.27 and 0.031 mm h^{-1}) and (0.42, 0.27 and 0.18 mm h^{-1}), respectively. The average width wear for indigenous blades (T4) and imported blades (T5) were (0.29, 0.18 and 0.021 mm h^{-1}) and 0.26, 0.17 and 0.016 mm h^{-1}, respectively. The study showed that the wear rate of the ADI blades were significantly more (due to improper mixing of elements *i.e.* nickel %) than those of the indigenous and imported blades.

Vuorinen *et al*. (2018) studied on erosive-abrasive wear behavior of carbide free bainitic and boron steels. The boron steels exhibited nominal lath martensite microstructure presented with laser microscope images. The wear surfaces were analyzed by scanning electron microscope. They concluded that the carbide free bainitic steels showed nearly 30% improved wear performance in comparison with the boron steels. The microcutting and microploughing were more dominating in the boron steel, whereas the carbide free bainitic steels had more shallow craters with thin platelets formed by repeated impacts. Due to the fact the carbide free bainitic steels showed smoother hardness profile than the boron steels.

Song *et al*. (2019) investigated the effect of nanobainite content on the dry sliding wear behavior of Al-alloyed high carbon steel. The wear test was carried out by pin – on disc tester. The pin was made from commercial quenched and tempered SAE52100 steel. The surfaces of all the samples before wear testing were ground to roughness of Ra=0.2μm. The results showed that, there were no significant differences in specific wear rate for samples with various amounts of nanobainite when the vertical load was 25 N. The specific wear rate gradually decreased as the nanobainite content in samples increased when the applied loads were 50 and 75 N). The optimum wear resistance was obtained for samples with 60 vol. % nanobainite.

2.2 Studies related to cryogenic treatment

Barron (1982) applied cryogenic treatment on metals to improve wear resistance. He tested twelve tool steels, three stainless steels and four other steels subjected to abrasive wear tests. The samples used in the abrasive wear tests were cylindrical, with a diameter of 12.7 mm and a length of 64 mm. Three sets of samples were used for each material tested *i.e.* a sample which was not given any cryogenic treatment after the usual heat treatment, a sample which was subjected to the cryogenic treatment (cooled slowly (3°C min^{-1}) from room temperature to 189 K) after the heat treatment as the control sample and a sample which was subjected to cryogenic treatment with some different parameters than the previous one (cooled slowly (3°C min^{-1}) from room temperature to 77 K) after the same heat treatment given to the control sample. The abrasive wear was tested on abrasive wear test operator in which the sample was fixed on loading arm (different weights attached here) and the end of the sample was pressed against coarse grit alumina grinding wheel and a stream of air was directed on end of sample for cooling. The results of this study indicated that wear resistance of tool steels significantly increased by subjecting the metal to a long soak (longer than 20 h) at temperatures of the order of 77 K. Here the lower temperature treatment was preferable than soak at 189 K, but for the stainless steels the 189 K soak was satisfactory in improving the wear resistance by as much as 25 %. Therefore, the wear resistance of plain carbon steels and cast iron was not significantly affected by the low-temperature treatment.

Lal *et al.* (2000) compared cryogenic treated and tin coated samples with help of flank wear test and sliding wear test. The cryogenic treated specimens for 24 h at 93 k were more effective on wear resistance than tin coating. The effect of cryogenic treatment on tin coating was not favorable which may be because of uneven contraction of the coating material *i.e.* cryogenic treatment should not follow tin coating. They also concluded that combination of tin coating with cryogenic treatment provides 45 % extended tool life than cryogenic treatment alone. The untempered samples when cryogenically treated at 133 K for 24 h yield 3 to 10 % extra life over tempered and cryogenically treated, but when tempered sample cryotreated at 93 K for 24 h showed the favorable results. Therefore, tempered samples if treated at lower temperature yield better results as compared to untempered cryotreated samples. The cryogenic treatment done at 93 k as per the prescribed cycle yields 20% extra life as compared to the maximum life achieved through cold treatment.

Molinari *et al.* (2001) studied the effect of deep cryogenic treatment on the mechanical properties of tool steels. The wear tests were carried out on Amsler trybotester (disk on disk geometry). The dry sliding tests were carried out by using a 100Cr6 steel hardened to 64 HRc as a counter face material with load 150 N, sliding speed 0.8 m s^{-1} for a total sliding distance of 5000 m. They concluded that deep cryogenic treatment increased the hardness and improves the hardness homogeneity, reduces the tool consumption and the down time for the equipments set up, thus leads to about 50 % cost reduction.

Zhirafar *et al*. (2007) investigated the effects of cryogenic treatment on the mechanical properties of 4340 steel. A group of specimens were subjected to conventional hardening including, austenitizing at 845°C for 15 min. in a tube furnace under flowing argon atmosphere, followed by oil quenching. Then tempering was carried out at three temperatures of 200, 300 and 450°C, using the same protective argon atmosphere for 2 h. Neutron diffraction was also used for measuring the retained austenite and martensite contents of the steel specimens before and after DCT. The instrument used for this measurement was the C2 DUALSPEC diffractometer located in the NRU reactor at Chalk River Laboratories, Ontario, Canada. They concluded that in 4340 steel components subjected to fatigue loading situations there was some beneficial effect of deep cryogenic treatment.

Baldissera and and Delprete (2008) reviewed various bibliographic on deep cryogenic treatment. They study treatment parameters (deep cryogenic treatment and shallow cryogenic treatment), effects on the material microstructure, effects on the mechanical properties. After investigating various experiments on cryogenic treatments they concluded that cryogenic systems allows to control important cycle parameters such as cooling rate, minimum reached temperature and soaking time. The choice of optimal treatment parameters requires specific investigations on each material under process. The wear resistance and hardness improvement have been widely confirmed by published papers, especially for the steel tools. Fine dispersed carbides precipitation appears to be more effective on the wear resistance DCT improvement of steels rather than the retained austenite elimination (in shallow cryogenic treatment). Fine carbides precipitation in tool steels due thermal stresses during cooling which leads to carbon atoms to segregate near lattice defects.

Pellizzari (2008) studied influence of deep cryogenic treatment on the properties of conventional and pm high speed steels. He measured hardness and fracture toughness before and after tempering to highlight the possible influence of deep cryogenic treatment. The wear tests were carried out using a dry sliding block on disc configuration. He studied properties of two wrought steels, HS6-5-2 (AISI M2) and HS6-5-2-5 (AISI M35). The HS6-5-2 steel showed a remarkable improvement in abrasive wear resistance without any increase in hardness due to cryogenic treatment. The most effective result was obtained by carrying out deep cryogenic treatment before tempering. The opposite occurs by HS6-5-2-5, containing about 4.8 % Co, whose wear resistance decreased in any treatment condition including deep cryogenic treatment. The steel showed a less significant change in properties, since these are mainly controlled by the high amount of evenly distributed primary carbides which are not highly influenced by deep cryogenic treatment. The cobalt seems to play a negative effect with respect to the low temperature conditioning of martensite.

Baldissera and Delprete (2009) studied effects of deep cryogenic treatment (DCT) on static mechanical properties of 18NiCrMo5 carburized steel and concluded that the soaking time parameter showed a strong influence on the mechanical properties *i.e.* hardness, tensile strength, compressive strength, wear rate *etc*. An assumption was give that the micro structural mechanism involves the entire process and further improvements could be possible with a prolonged deep cryogenic treatment exposure.

Kalsi *et al*. (2010) reviewed cryogenic treatment of tool materials. They focused on the main parameters *i.e*. temperature, soaking period, cooling rate *etc*. They concluded that deep cryogenic treatment has favorable influences on the performance of steels. This could be a good alternative for improving performance, depending on the application enhancement. The complete process must follow the order austenitization, quenching, cryogenic treatment, and tempering to get better results. Depending on the properties of the material with lowest possible soaking temperature in cryogenic treatment, are preferred in order to achieve maximum wear resistance. A period of about 1 h with lowest temperature is sufficient to enhance fatigue load resistance. The contribution of cryogenic treatment to improve the wear resistance is due to martensite, carbide formation, and homogeneous distribution of produced carbides rather than only removal of retained austenite.

Koneshlou *et al*. (2011) carried out study on the effect of cryogenic treatment on microstructure, mechanical and wear behaviors of AISI H13 tool steel rod (C- 0.36, Mn- 0.38, Si -0.96 Cr- 4.82 Mo- 1.19 V- 0.86 P- 0.017). The mechanical properties of samples were measured using an Instron 4400 machine. The hardness was measured using wolpert HRC hardness tester. The deep cryogenic treatments of samples were performed by placing specimens in an isolated chamber at temperature of -196^{o}C. The results showed that the deep cryogenic treatment to conventional heat treatment processes help to achieve more resistant able tool steel parts, because due to the deep cryogenic treatment at a very low temperature and holding the samples for a long time resulted in precipitation of very fine and more uniform distribution of carbide particles in the microstructure. Applying lower temperatures also lead to smaller and more uniform martensite laths in the microstructure, however the most important effect of the deep cryogenically treated samples was the improving of the wear properties of the H13 tool steel.

Jagtar *et al.* (2013) studied on wear resistance of En-45 spring steel using cryogenic treatment. EN-45 spring steel is used for manufacturing the main components of cultivator. The tests were carried out separately for three different treatments. The conventional heat treated (CHT) steel samples at 950 ^{o}C, shallow cryogenic treated samples at -90 ^{o}C and deep cryogenic treated samples at -184 ^{o}C . The hardness of the samples is measured with Vickers hardness test.

This instrument has a square-based diamond pyramid with an angle of 136 ^{o} between opposite faces. The hardness values were taken corresponding to the diagonal length. The result showed that the hardness for conventional heat treated samples, shallow cryogenic treated samples and deep cryogenic treated samples was 54, 56 and 57, respectively. It was clear from the results that the deep cryogenic treatment has the more hardness as compared to other treatments. There was significant increase in average wear resistance of deep cryogenic treatment such as 70 % over shallow cryogenic treatment and 154 % over conventional heat treatment.

Li *et al*. (2016) studied the influence of deep cryogenic treatment on the microstructure, hardness, impact toughness and abrasive wear resistance of high-vanadium alloy steel. They concluded that by increasing the deep cryogenic processing time and cycle number, impact toughness and abrasive wear resistance improved, the carbide contents continuously increased, and the hardness decreased. After deep cryogenic treatment, there were a large amount of dispersed carbide precipitation, secondary carbide ever increasing due to the increased deep cryogenic processing time and number of cycles. Therefore, deep cryogenic treatment decreased the hardness and increased the impact toughness as compared to those of the conventional treatment, which was attributing to the carbon content in the martensite decreasing after deep cryogenic treatment.

Kumar *et al*. (2017) reviewed on influence of cryogenic treatment on the metallurgy of ferrous alloys. They concluded that considerable quantity of retained austenite exists after regular heat treatment and cryogenic treatment is effective in the elimination of retained austenite. With cryogenic treatment there is a substantial increment in hardness and wear resistance and the formation of strain induced brittle martensite was prevented as well. In addition to the removal of retained austenite, cryogenic treatment brings about uniform distribution and fine precipitation of secondary carbides. With respect to the treatment temperature, reducing the treatment temperature does not increase the precipitation of carbides, as below -196˚C diffusion of carbides and mobility of the dislocations slows down. Precipitation of secondary carbides is an isothermal process and beyond a threshold time limit, carbide precipitates grow bigger and the population intensity begins to decrease. Some studies otherwise suggest, carbon atoms are immovable at cryogenic conditions and it is the moving dislocations which capture the carbon atoms. While several studies report that cryogenic treatment affects the entire material. They concluded that more research can be carried out to apply cryogenic on ferrous materials and coatings with a view to improve the mechanical properties and the performance of these materials used for cutting purpose.

Singla *et al*. (2018) reviewed on processing of materials at cryogenic temperature and its implications in manufacturing. They point out that the cryogenic processing of cutting tools and work piece material has also emerged as a potential technique for improving the performance of cutting tools during metal cutting as well as for improving the machinability and weldability of work piece materials. After reviewing many literatures they concluded that the soaking time in the range of 13–24 h is recommended by majority of the past studies for HSS, stainless steel, and other alloy steels, but a large number of researchers recommended soaking time in the range of 0–12 h for cold and hot work tool steels, cemented carbides, and nonferrous materials. Since the cost of CT is decided largely by soaking time, it is proposed to explore the optimum soaking time for cold and hot work tool steels, cemented carbides, and nonferrous mater. The cooling rate during cryogenic treatment in the range of 0.25–2 K min^{-1} was recommended by most of the researchers. The cryo-treated workpiece materials lead to reduction in shear resistance, tangential wear resistance, increase tensile strength *etc*. of metal used in cutting operations. So there is an urgent need of bringing more materials in the ambit of this area of research and thereby opening a huge scope of work in the area of metal.

Singh *et al*. (2020) studied on abrasive wear behavior of cryogenically treated boron steel (30MnCrB4) used for rotavator blades. They selected low carbon boron steel (DIN 30MnCrB4), which was widely used in rotavator blades. The chemical composition of material was tested using optical emission spectrometer. Firstly the specimens prepared as per ASTM standards then deep cryogenic treatment (-185˚C/12h) followed by austenitizing (900˚C/0.67h). After that various mechanical properties and economic analysis were done. The study concluded that during deep cryogenic treatment, retained austenite left was transformed into martensite. Cryogenic treatment also resulted in formation of secondary carbides and helped in bringing more uniformity in distribution of secondary carbides. Hardness of cryo-treated specimen was improved by 206.73 % compared to untreated material, due to the formation of martensite along with the precipitation of secondary carbides. Impact strength of the cryo-treated specimen was augmented by 50 % in comparison with treated specimen, due to increasing the nucleation of carbides, which facilitated the precipitation of a higher number of fine carbides during cryogenic treatment, resulting higher impact strength of material. The abrasive wear volume loss in cryo-treated specimens was reduced by 60 % as compare to untreated samples. The additional cost of 15.12 % was incurred due to cryogenic treatment.

CHAPTER-III

MATERIALS AND METHODS

The crops are mostly harvested with the help of combine, straw reaper, thresher *etc*. The cutting blades used in these harvesting machines are made up of high carbon steels, but with long working hours, these blades face certain problems which are associated with their life. Due to the increasing temperature with continuous working, these blades start facing high wear rate which causes edge breakage. Therefore, the main objective of this study is to deal with decreasing blade life. The study was planned and conducted in the following sequence:

3.1 Selection of material
3.2 Deep cryogenic treatment
3.3 Wear analysis
3.4 Metallurgical investigation
3.5 Economic analysis

3.1 Selection of material

In the present study, two types of testing were performed *viz*. lab testing and field testing. For the lab testing, the high carbon steel in the form of cylindrical shape specimens were used and for field testing cutter bar blade (A type) and chopping cylinder blade (M type) were used in straw combine. The high carbon steel blades widely used in straw combine were used in the study. The blades used in the study were manufactured by Marshall Company and purchased from Shiv Narian & Sons, Automobile Market, Hisar, Haryana. The composition of high carbon steel materials is shown in Table 3.1.

Table 3.1 Composition of high carbon steel

Sr. No.	Constituents	Weight %
1	Carbon	0.856
2	Silicon	0.250
3	Manganese	0.640
4	Sulphur	0.007
5	Phosphorous	0.020
6	Chromium	0.079

3.1.1 Preparation of specimens

i. A high carbon steel rod was used for the preparation of specimens.
ii. The long high carbon steel rod initially converted into smaller length so that it can be easily operated on the lath machine.
iii. Now, the diameter of high carbon steel rod reduced with the help of turning operation on lathe machine (Fig. 3.1).

iv. After turning operation, further high carbon steel rod was cut in order to obtain the length of 35 mm for each specimen with help of hand hacksaw (Fig. 3.2).

v. The finishing of specimen was performed with the help of hand file and emery paper in order to provide smooth surface.

Fig. 3.1: Turning of high carbon steel rod

Fig. 3.2: Cutting of high carbon steel rod

3.1.2 Dimensions of specimens

The dimensions of the specimens were measured with the help of digital vernier scale. A vernier scale is a micrometer by which a job is measured on its outer diameter, inner diameter and depth. The length and diameter of the working specimens was taken as 35 and 10 mm, respectively.

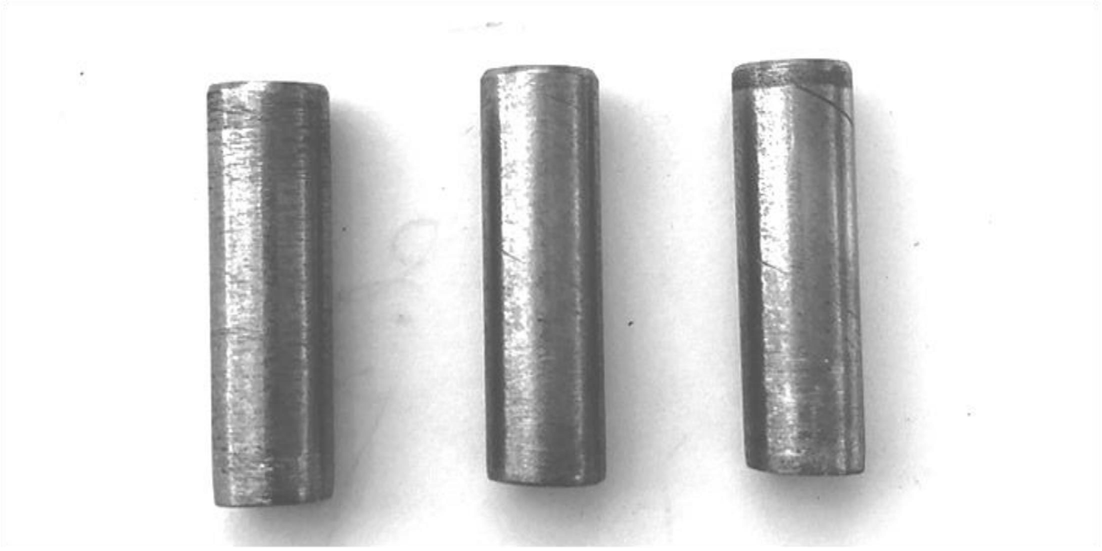


Fig. 3.3: High carbon steel specimens

3.2 Cryogenic treatment

The basic cryogenic treatment comprises of gradual cooling of the component until the defined temperature, holding it for a given time (freezing time) and then progressively leading it back to the room temperature. The aim is to obtain an improvement of mechanical properties, hardness, wear resistance and toughness. Cryogenic treatment is mainly two types, shallow cryogenic treatment (-80°C to -140°C) and deep cryogenic treatment (-180°C to -196°C). Deep cryogenic treatment undergo with following parameters:

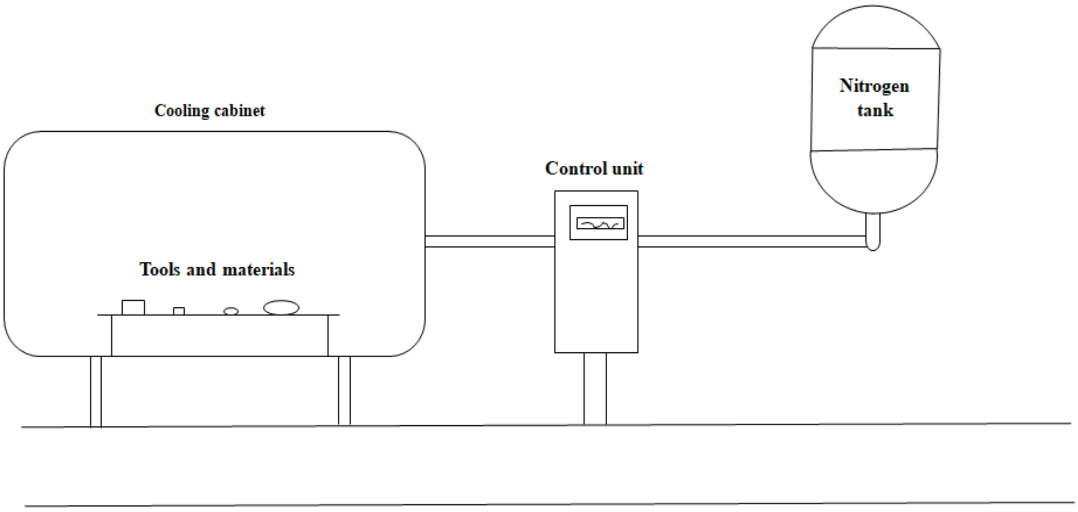


Fig. 3.4: Cryogenic treatment procedure

3.2.1 Cryogenic parameters

3.2.1.1 Soaking temperature

Soaking temperature is the final required temperature at which specimen is kept to soak for the fixed time of duration. In case of deep cryogenic treatment, temperature ranges from -180 °C to -196°C.

3.2.1.2 Rate of cooling

It is the rate at which the required temperature for the treatment was achieved *i.e.* the rate at which the temperature of specimens decreased from room temperature to the required deep cryogenic treatment temperature.

3.2.1.3 Soaking period

Soaking period is the time up to which we have to keep the specimens at the deep cryogenic required temperature. It is most effective factor in cryogenic treatment. In order to achieve better results, the soaking period must be at optimum level. Generally twelve hour is efficient for deep cryogenic treatment.

3.2.1.4 Heating rate

It is the rate at which the specimen's deep cryogenic temperature *i.e.* -196°C of specimens brought back to the room temperature *i.e.* 35°C.

In the present study the deep cryogenic treatment was conducted using cryogenic processor provided by Kryo Space Pvt. Ltd., Pune, Maharashtra, India. Cryogenic treatment set up was brought to the desired temperature using computer controls in a well insulated chamber with liquid nitrogen as working medium.

Table 3.2 Deep cryogenic treatment process parameters

Sr. No.	Parameters	Value
1	Soaking temperature(°C)	-190°C
2	Cooling temperature (°C min^{-1})	1
3	Soaking period (h)	16
4	Heating rate(° min^{-1})	1

3.3 Wear analysis

The wear test was carried out to analyze wear property of material to determine whether the material is adequate for a specific wear application. From surface engineering point of view, the wear analysis was carried out to evaluate the potential of material using a certain surface engineering technology. The objective was to reduce wear for a specific application and to investigate the effect of treatment conditions on the wear performance so that an optimized surface treatment conditions can be realized. In the present study, the wear analysis was carried out at field as well as in laboratory.

3.3.1 Wear analysis in laboratory

The laboratory testing was done in Tribology and Vibration laboratory of Mechanical Engineering Department, UIET, Kurukshetra University, Kurukshetra, Haryana. The test specimens of high carbon steel having diameter of 10 mm and length of 35 mm was used for abrasive wear testing. The specimens used for wear analysis were categorized as cryo-coated specimens and uncoated specimens.

3.3.1.1 Pin on disc working procedure

Before wear analysis the specimen's surface was first cleaned with acetone. The specimens were kept for a while so that the acetone on its surface blown away. After that, the specimens were dried and cleaned with tissue paper to remove unwanted dust particles, foreign particles *etc*. By doing this we will get the exact weight of the specimens. After that, the weight of the specimens was measured with the help of electronic weighing scale with least count of 0.0001g (Fig. 3.5).

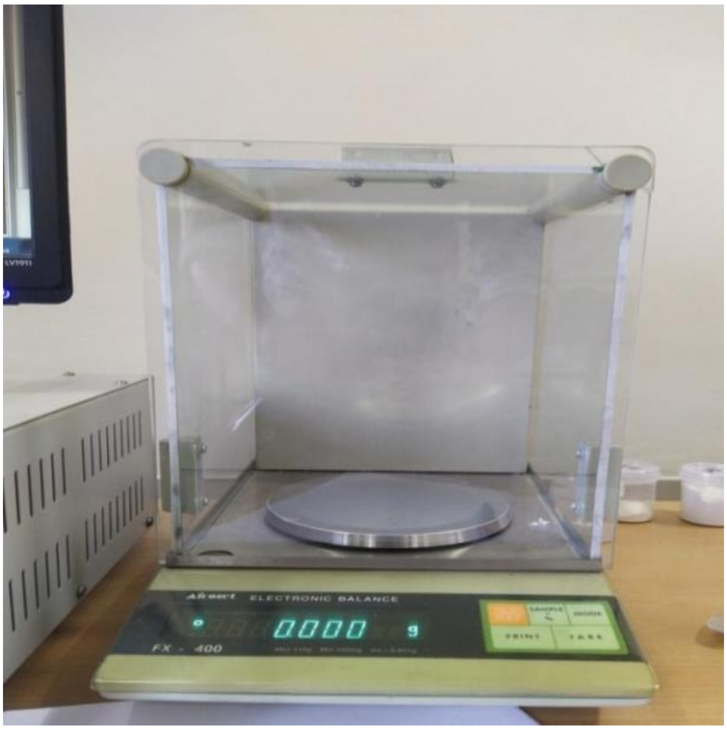


Fig. 3.5: Electronic weighing scale

The wear analysis was performed with the help of a pin on disc wear tester (Fig. 3.6), in which a pin (specimen) loaded against a flat rotating disc (the counter surface). This machine can be used to evaluate wear and friction properties of materials under pure sliding conditions. The commercially available materials such as bearing steels, tungsten carbide etc. used as counter face. Before starting the testing machine, the sample was installed in the holder by set screw and then pressed under vertical load. The parameters selected for wear analysis are shown in Table 3.3. The specifications of pin on disk wear tester are shown in

Table 3.4. The values of load, sliding velocity, time were selected with wear and friction monitor apparatus control unit (Fig. 3.7) to emulate the actual required conditions. The weight of each specimen, before and after the experiment was checked by using weighing balance (Fig. 3.5) with a least count of 0.0001g. The experimental plan was based on Taguchi's methodology (Reddy, 2001). The Taguchi's L_9 orthogonal array for the wear analysis is shown in Table 3.5.

Table 3.3 Parameters and their levels for wear analysis

Sr. No.	Parameters	Levels
1	Load (N)	15, 20, 25
2	Sliding velocity (m s^{-1})	1.31, 2.61, 3.92
3	Time (s)	150, 300, 450

Table 3.4 Specifications of the Pin-on-disc wear testing machine

Sr. No.	Particulars	Specifications
1	Pin on disc	Ducom TR 20 LE
2	Disc material	EN 31 steel disc hardened to 64 HRC
3	Disc size, mm	165 diameter
4	Track diameter, mm	0 - 120
5	Speed, rpm	0 - 2000
6	Speed, m s^{-1}	0 - 12560
7	Normal load, kg	0 - 20
8	Drive	1.1 KW DC motor with constant Torque
9	Power supply	230V, 15A Single phase 50 Hz AC
10	Software	Winducom 2010

Table 3.5 Experimental plan using L_9 orthogonal array

Sr. No.	Load (N)	Sliding velocity (m s^{-1})	Time (s)
1	15	1.31	150
2	15	2.61	300
3	15	3.92	450
4	20	1.31	300
5	20	2.61	450
6	20	3.92	150
7	25	1.31	450
8	25	2.61	150
9	25	3.92	300

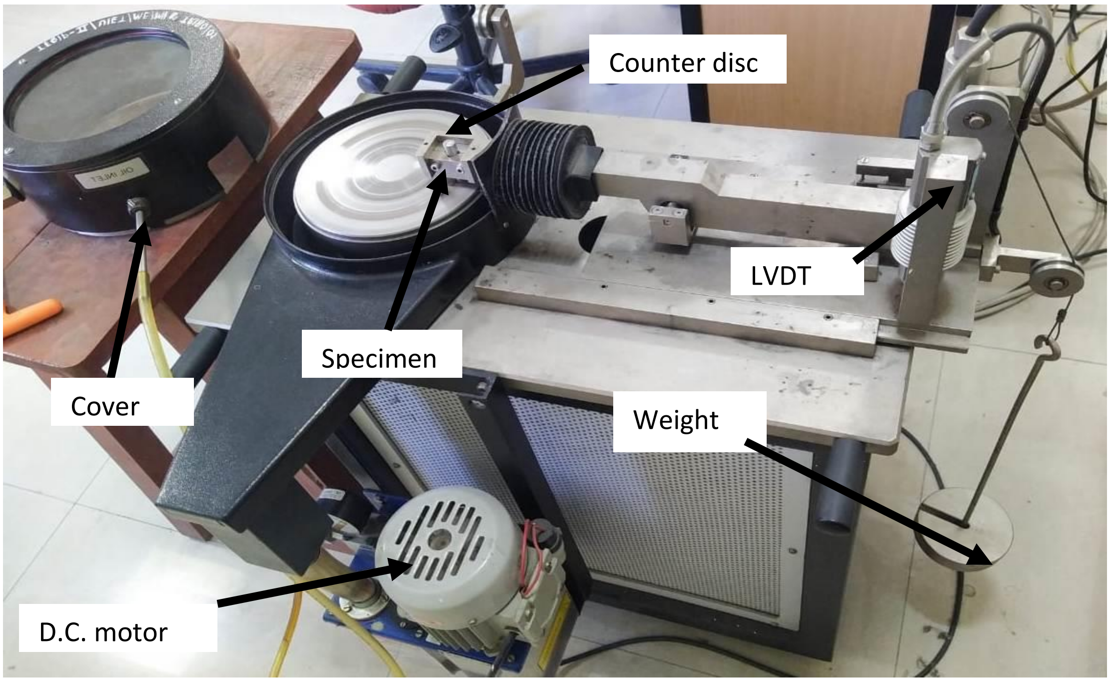


Fig. 3.6: Pin on disc wear tester

Fig. 3.7: Pin on disc control unit

3.3.1.2 Specific wear rate

Wear is the damaging, gradual removal or deformation of material at solid surfaces and the study of wear and related processes are referred to tribology. The specific wear rate is the amount of wear loss per unit distance per unit load. The SWR can be calculated as wear loss divided by the product of sliding distance, density of material and normal load.

$$SWR = M/\rho LS$$

Where,

M is the total mass loss, g

L is the normal load, N

ρ is the density of material used in this work, g cm^{-3} (7.85)

S is the sliding distance, m

SWR, mm^3 Nm^{-1}

3.3.2 Wear analysis at field

The high carbon steel blades were installed in straw combine. 'A' type blades were used in the cutter bar and M type blades were used in the chopping cylinder of the straw combine. All the field work was carried on the fields of village Ludas and Shahpur Hisar, Haryana. The straw reaper used for the field work was manufactured by Jaswant Agriculture Works Pvt. Ltd., Sangrur, Punjab.

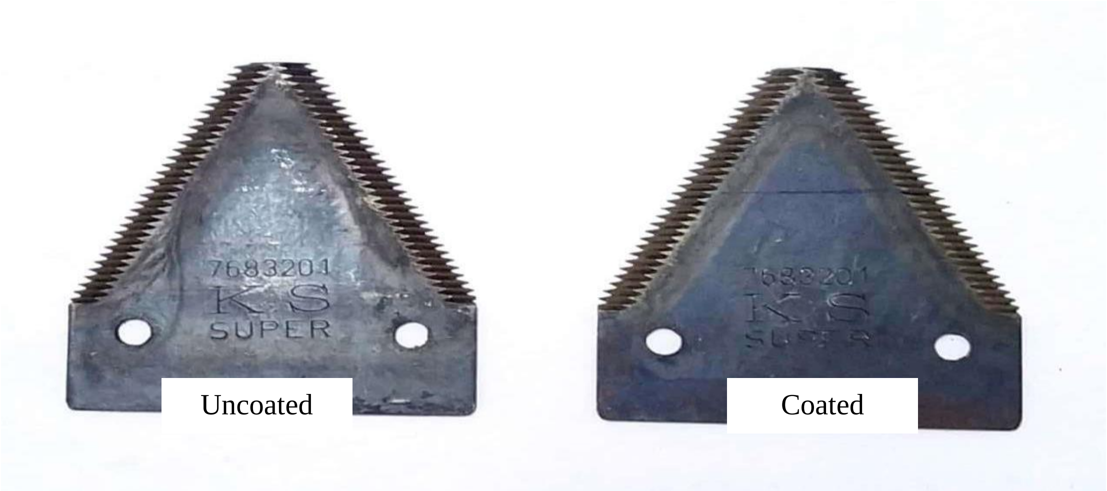


Fig. 3.8: A –type blade (Cutter bar)

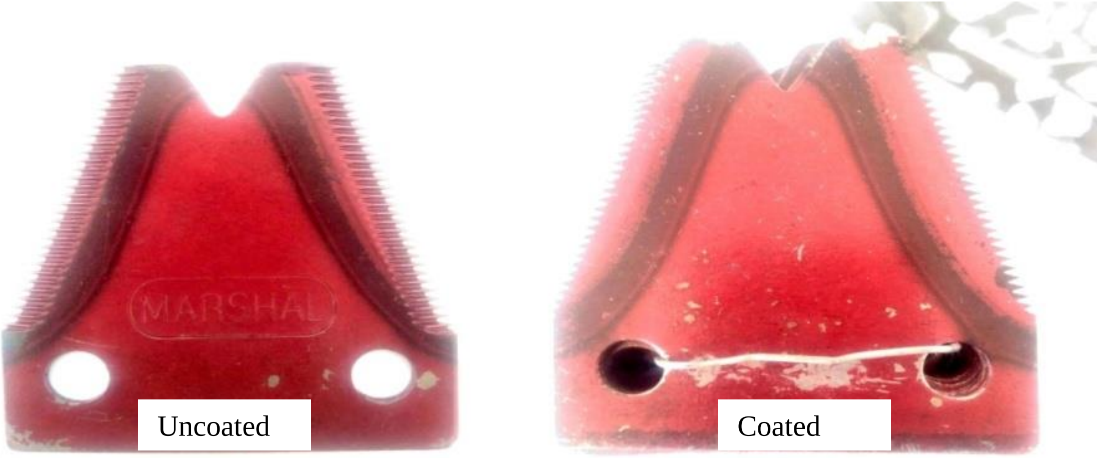


Fig. 3.9: M –type blade (Chopping cylinder)

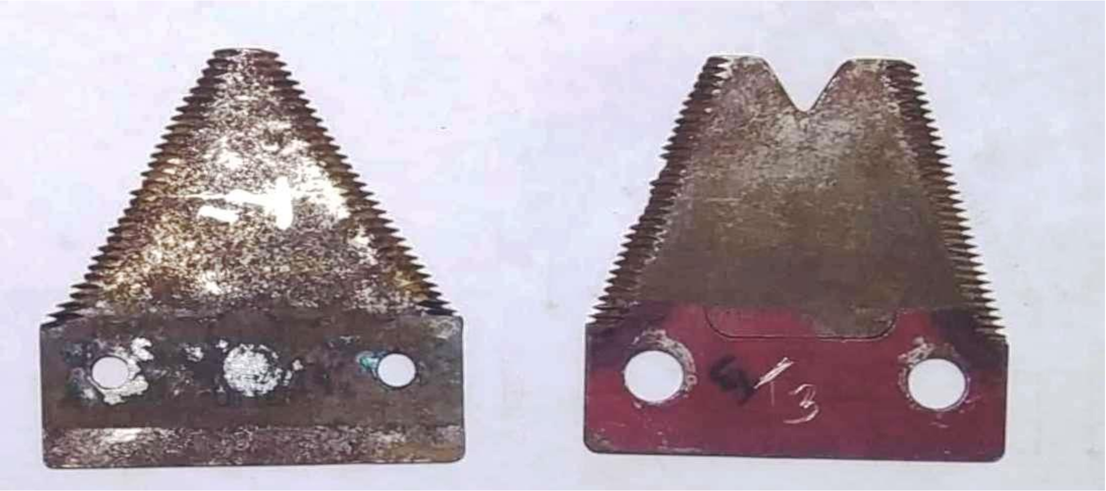


Fig. 3.10: Coated blades after work

Fig. 3.11: Uncoated blades after work

3.3.2.1 Procedure of experiment

A total of 20 blades were used for the field testing, out of which 10 blades were of A-type and 10 blades were of M- types. In each type, half of the blades were cryo-coated and half of the blades were uncoated.

3.3.2.2 Installation of blades

i. Cutter bar blade (A-type)

Generally a cutter bar of straw combine has 30 blades. For the experimental purpose 10 blades were installed on the cutter bar out of which 5 were coated and 5 were uncoated blades. These 10 blades were installed in such a way that the wear of the entire cutter bar blades can be predicted. The position numbers of the blades were noted down so that later on blades can be readily indentified.

Table 3.6 Position of coated blades on cutter bar

Coated	Place number
C_1	5
C_2	9
C_3	13
C_4	17
C_5	21

Table 3.7 Position of uncoated blades on cutter bar

Uncoated	Place number
UC_1	6
UC_2	10
UC_3	14
UC_4	18
UC_5	22

Fig. 3.12: Position of coated and uncoated blades on cutter bar (A type)

ii. Chopping cylinder blade (M type)

The chopping cylinders of straw combine usually have 304 blades. These 304 blades are mounted on 16 flat plates in the chopping cylinder, which means there are 19 blades on each plate. For experimental purpose 10 blades were taken, out of which 5 were uncoated and 5 were coated blades. These 10 blades were placed in such a way so that collective wear of the entire blades can be observed. For easy identification of the blades later, blades were marked with permanent marker on the side where bolts are rooted to fix the blades.

Fig. 3.13: Position of coated and uncoated blades (M type) in chopping cylinder

Fig. 3.14: Straw combine machine in operation in the field

3.3.3 Wear analysis with respect to weight

The weight of both cutter bar blade (A type) and chopping cylinder blade (M type) were measured before installing on the straw combine. After that, the straw combine was continuously driven for 38.33 hours in the field. The weight of each blade was measured after testing of straw combine.

Fig. 3.15: Weighing of blades

Now the wear amount was carried out by using formula:

$W = W_1 - W_2$

W is the wear amount (g)

W_1 is the weight before test (g)

W_2 is the weight after test (g)

Wear percentage was carried out for the comparison of wear out between cryogenic coated and uncoated

$$\text{Wear percentage (W \%)} = \frac{W}{W1} \times 100$$

Where,

W is the wear amount (g)

W_1 is the initial weight of the blade (g)

3.3.4 Wear analysis with respect to the dimensions

In dimension wear analysis method, the wear of the blades were measured on the basis of dimensions of blades. All dimensions were measured with help of vernier caliper (Fig. 3.16). In this method, the initial dimensions of blades were compared with the dimensions of the blades after the field testing of straw combine.

Fig. 3.16: Digital vernier caliper

The dimension analysis was performed as:

i. First of all reset the vernier caliper.

ii. Now, mark a straight line 30 mm down from the tip of the blade with the help of digital vernier scale.

iii. Now, measure the width of the blade at this 30 mm depth.

iv. After that measure the width of the blade at the tip point of blade with help of digital vernier scale.

v. At last measure the height of whole blade *i.e.* from the tip of the blade to the bottom of the blade.

Fig. 3.17: Measurement of dimensions of blades (A and M type)

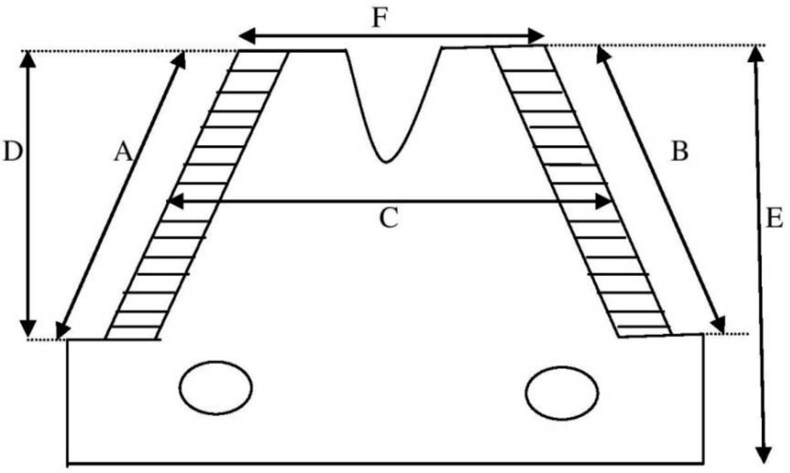


Fig. 3.18: Dimensions of chopping cylinder blade (M type)

A	58 mm
B	58 mm
C	60 mm
D	53 mm
E	81 mm
F	38.30 mm

Where,

A and B are the slant height of cutting section of blade.

C is the width of blade at 30 mm from the tip point.

D is the height of cutting section of blade.

E is the total height of blade.

F is the width of blade at tip.

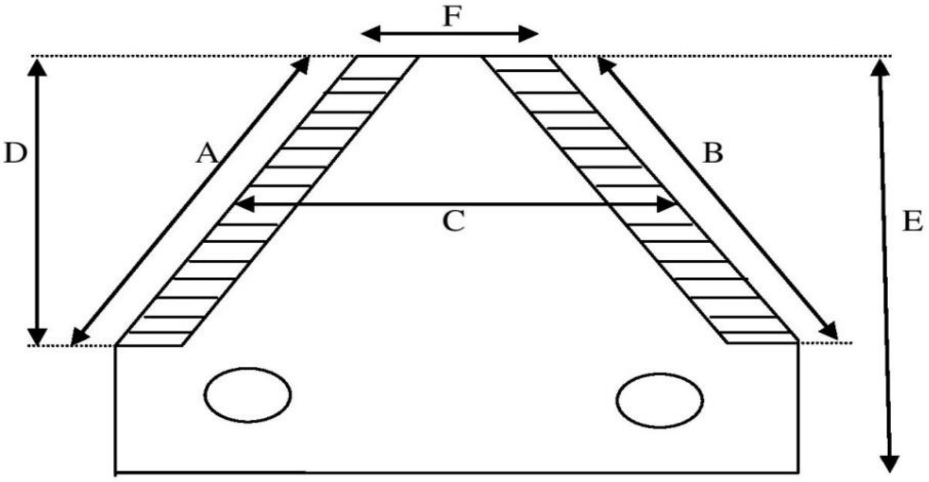


Fig. 3.19 Dimensions of cutter bar blade (A type)

A	65 mm
B	65 mm
C	50.28 mm
D	54.5 mm
E	84 mm
F	14.40 mm

Where,

A and B is the slant height of cutting section of the blade.

C is the width of blade at 30 mm from the tip point.

D is the height of cutting section of blade.

E is the total height of blade.

F is the width of the blade at tip point.

Wear (%) was calculated as:

i. With respect to length/ height of the blade

$$\text{Wear percentage (W \%)} = \frac{\Delta l}{L} \times 100$$

Where,

Δl is change in dimensions after work (mm)

L is original dimensions of blade before work (mm)

ii. With respect to the width of the blade at the tip

$$\text{Wear percentage (W \%)} = \frac{\Delta b}{B} \times 100$$

Where,

Δb is change in width of the blade (At tip) (mm)

B is width of the blade at tip before experiment (mm)

iii. With respect to the width of the blade at 30 mm (from tip of blade)

$$\text{Wear percentage (W \%)} = \frac{\Delta b30}{B} \times 100$$

Where,

Δb_{30} is change in width of blade at 30 mm from tip of blade (mm)

B is width of the blade at 30 mm before experiment (mm)

3.4 Metallurgical investigation

3.4.1 Field Emission Scanning Electron Microscope (FE-SEM)

Metallurgical investigation was done with the help of Field Emission Scanning Electron Microscope (FE-SEM). It is an electron microscope that produces images of a sample by scanning the sample with the beam of electrons which contains the information about the surface topography and composition. The electrons are produced by a thermal emission source, such as a heated tungsten filament, or by a field emission cathode. The energy of the incident electrons can be as low as 100 ev or as high as 30 kev depending upon the evaluation objectives. The electrons are focused into a small beam by series of electromagnetic lenses. Scanning coils near the end of the column position and direct the focused beam on the sample surface. The beam can also be focused to single point for x- ray analysis. The beam can be focused to a final diameter as small as about 10 Å. The incident electrons cause electrons to be emitted from the sample due elastic and inelastic scattering events within the sample's surface. Some high-energy electrons that are rejected by an elastic collision of an incident electron with nucleus of atom of the sample and these electrons are referred to as backscattered electrons. The lower-energy electrons resulting from inelastic scattering are called secondary electrons. The energy of the secondary electrons is typically 50 ev or less.

Fig. 3.20 Field Emission Scanning Electron Microscope (FFE-SEM)

To create an SEM image, the incident electron beam is scanned in a raster pattern across the sample's surface. The emitted electrons are detected for each position in the scanned area by an electron detector. The intensity of the emitted electron signal is displayed as brightness on a cathode ray tube (CRT). By synchronizing the CRT scan to that of the scan of the incident electron beam, the CRT display represents the morphology of the sample surface area scanned by the beam. Magnification of the CRT image is the ratio of the image display size to the sample area scanned by the electron beam. In SEM two types of detector are used for imaging. For secondary electrons imaging, scintillator type are used. Detectors for the backscattered electrons can be scintillator or a solid-state detector. The SEM sample chamber are at moderate vacuum to allow the electrons to travel freely from the electron beam source to the sample and then to the detectors. High-resolution imaging is done with the chamber at higher vacuum, typically from 10^{-5} to 10^{-7} Torr.

3.5 Economic analysis

Economic analysis was done to evaluate the expected improvement in performance of straw combine blade during field operation against the additional cost quantified in Indian Rupees (Rs.) due to cryogenic treatment. The details of economic analysis are as follows:

1. First of all determine the average cost of blade required in straw combine.
2. Average life of the blade without cryogenic treatment.
3. Cost of cryogenic treatment per blade. For cost of cryogenic treatment flowing steps were followed:

i. Find cost of cryogenic treatment per kg.

ii. Find the average weight of cutter bar blade and chopping cylinder blade (g).

iii. Now find cost of cryogenic treatment per blade with respect to average weight (g) of the blades.

$$cost\ of\ cryogenic\ treatment\ per\ gram \times average\ weight\ of\ blades (g)$$

4. Average life of the blade after cryogenic treatment. To find average life of blades flowing steps were followed:

i. First find out the wear (%) for all cutter bar (coated & uncoated) and chopping cylinder (coated & uncoated) blades.

$$\text{Wear (\%)} = \frac{Weight\ loss\ (g)}{Initial\ weight\ (g)} \times 100$$

ii. Now use this average of wear (%) to find how much wear is less in cryogenic coated blades.

$$\frac{Wear\ (\%)\ (untreated - treated)}{Wear\ (\%)\ untreated} \times 100$$

iii. With respect to the (ii) point value (amount of less wear) finds out blade’s life.

$$Amount\ of\ less\ wear (\%) \times Life\ ofblade\ without\ treatment (h)$$

5. Percentage increase in life per blade due to cryogenic treatment.

i. By comparing initial life (h) of blade and life after treatment (iiird point), the % increase in life of blade can be calculated.

6. Percentage increase in cost of blade after cryogenic treatment:

i. By comparing initial cost (fixed) and cost after treatment (iind point), the % increase in cost of blade after treatment can be calculated.

ii. The cost of a blade per hour was also calculated. For this, the cost of blade divided by life of blade (before and after the cryogenic treatment) was calculated.

CHAPTER-IV

RESULTS

In the present study the wear results obtained from laboratory and field experiments were presented. In laboratory experiments, the results were carried out with the help of pin on disc experimental unit and the filed experiments results were carried out with the help of tractor operated straw combine. The results of the experiments were presented in this chapter with the help of appropriate tables, graphs and figures under the following major headings:

4.1 Wear testing (Pin on disc)
4.2 Wear testing (Field)
4.3 Field Emission Scanning Electron Microscopy
4.4 Economic Analysis

4.1 Wear testing (Pin on disc)

In this phase of study, the effect of cryogenic treatment on the wear of high carbon steel specimen was observed in laboratory by using pin on disc wear testing machine. Test specimens classified as coated and uncoated were mounted on the machine disc for continuous sliding. The operating load, sliding velocity and time were taken as 15, 20, 25 N; 1.31, 2.61, 3.92 m s^{-1} and 150, 300, 450 s, respectively.

4.1.1 Effect of Load and sliding velocity on wear

The effect of load and sliding velocity are presented in Table 4.1 and Fig. 4.1 to 4.3. As the load increased from 15 to 25 N at constant velocity of 1.31m s^{-1}, the wear of the blades increased from 0.0010 to 0.0033 and 0.00080 to 0.00177 g in uncoated and coated specimens, respectively. Similarly, at 2.61 m s^{-1}, the wear of the specimen increased from 0.0020 to 0.0035 and 0.00110 to 0.0182 g for uncoated and coated, respectively. At 3.92 m s^{-1}, as the load increased from 15 to 25 N, the wear increased from 0.0024 to 0.0050 and 0.00131 to 0.00199 g for uncoated and coated specimen, respectively.

Table 4.1 Effect of load on wear at different constant velocity

Sr. No.	Velocity (m s^{-1})	Load (N)	Wear (g)		Change (%)
			Uncoated	Coated	
1	1.31	15	0.0010	0.00080	44.80
2		20	0.0025	0.00138	46.30
3		25	0.0033	0.00177	45.00
4	2.61	15	0.0020	0.00110	43.33
5		20	0.0027	0.00153	48.00
6		25	0.0035	0.00182	45.41
7	3.92	15	0.0024	0.00131	41.07
8		20	0.0028	0.00165	60.02
9		25	0.0050	0.00199	20.00

4.1.2 Effect of sliding velocity and load on wear

The effect of sliding velocity and load are presented in Table 4.2 and Fig. 4.4 to 4.6. As the sliding velocity increased from 1.31 to 3.92 m s^{-1} at constant load of 15 N, the wear of the blades increased from 0.0010 to 0.0024 and 0.00080 to 0.00131 g in uncoated and coated specimens, respectively. Similarly, at 20 N load, the wear of the specimen increased from 0.0025 to 0.0028 and 0.00138 to 0.00165 g for uncoated and coated, respectively. At 25 N load, as the sliding velocity increased from 1.31 to 3.92 m s^{-1}, the wear increased from 0.0033 to 0.0050 and 0.00177 to 0.00199 g for uncoated and coated specimen, respectively.

Table 4.2 Effect of sliding velocity on wear at different constant loads

Sr. No.	Load (N)	Sliding velocity (m s^{-1})	Wear (g)		Change (%)
			Uncoated	Coated	
1	15	1.31	0.0010	0.00080	20.00
2		2.61	0.0020	0.00110	45.00
3		3.92	0.0024	0.00131	45.41
4	20	1.31	0.0025	0.00138	44.48
5		2.61	0.0027	0.00153	43.33
6		3.92	0.0028	0.00165	41.07
7	25	1.31	0.0033	0.00177	46.30
8		2.61	0.0035	0.00182	48.00
9		3.92	0.0050	0.00199	60.02

4.1.3 Effect of sliding distance and load on wear

The effect of sliding distance and load are presented in Table 4.3 and Fig. 4.7 to 4.9. As the sliding distance increased from 196.50 to 1764 m at constant load of 15 N, the wear of the blades increased from 0.0010 to 0.0024 and 0.00080 to 0.00131 g in uncoated and coated specimens, respectively. Similarly, at 20 N load, the wear of the specimen increased from 0.0025 to 0.0028 and 0.00138 to 0.00165 g for uncoated and coated, respectively. At 25 N load, as the sliding distance increased from 273.79 to 2446 m, the wear increased from 0.0033 to 0.0050 and 0.00177 to 0.00199 g for uncoated and coated specimen, respectively.

Table 4.3 Effect of sliding distance on wear at different constant loads

Sr. No.	Load (N)	Sliding distance (m)	Wear (g)		Change (%)
			Uncoated	Coated	
1	15	196.50	0.0010	0.00080	20.00
2		783.00	0.0020	0.00110	45.00
3		1764.00	0.0024	0.00131	45.41
4	20	393.00	0.0025	0.00138	44.48
5		588.00	0.0028	0.00165	41.07
6		1174.00	0.0027	0.00153	43.33
7	25	273.79	0.0033	0.00177	46.30
8		1085.76	0.0035	0.00182	48.00
9		2446.08	0.0050	0.00199	60.02

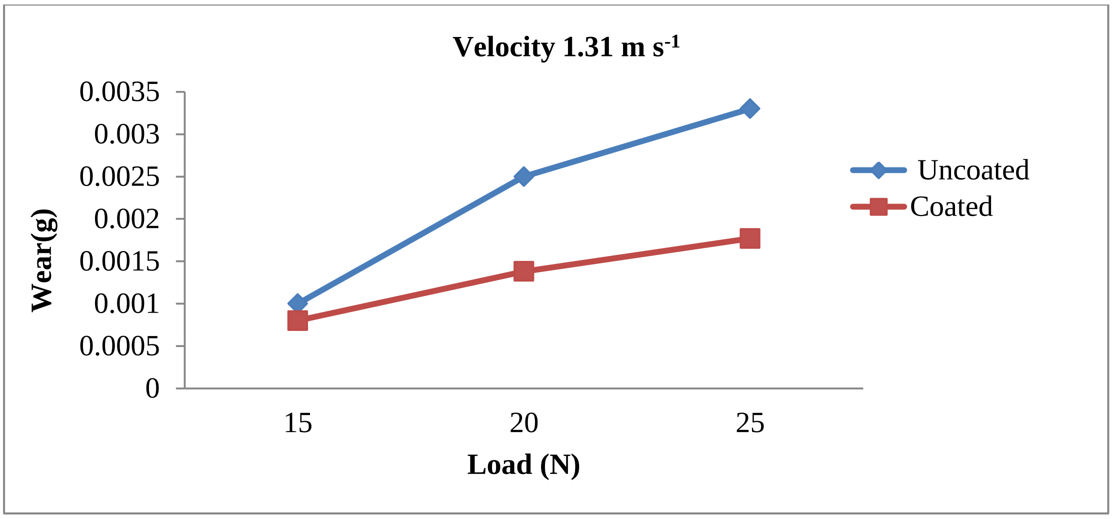


Fig. 4.1: Effect of load on wear at 1.31 m s^{-1} velocity

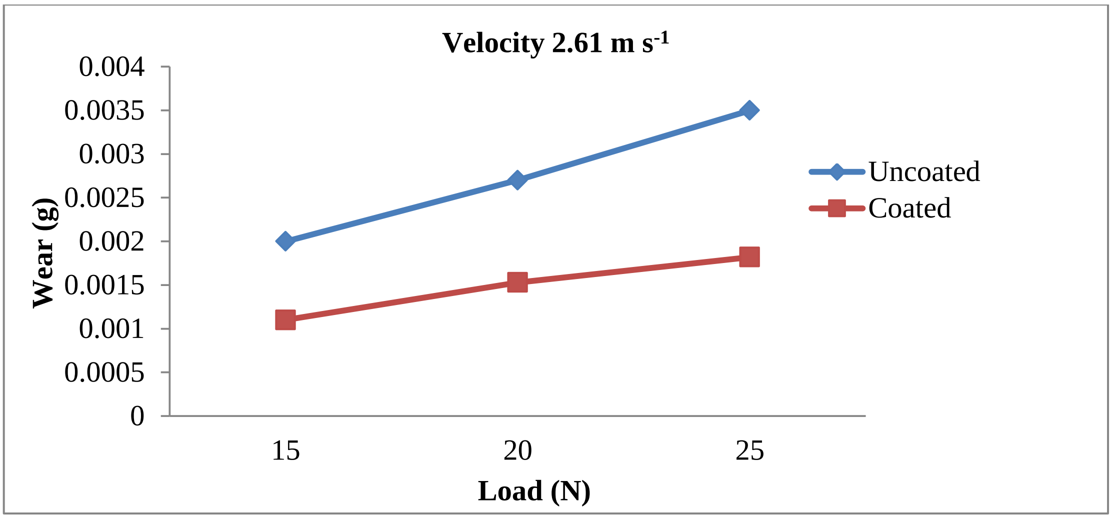


Fig. 4.2: Effect of load on wear at 2.61 m s^{-1} velocity

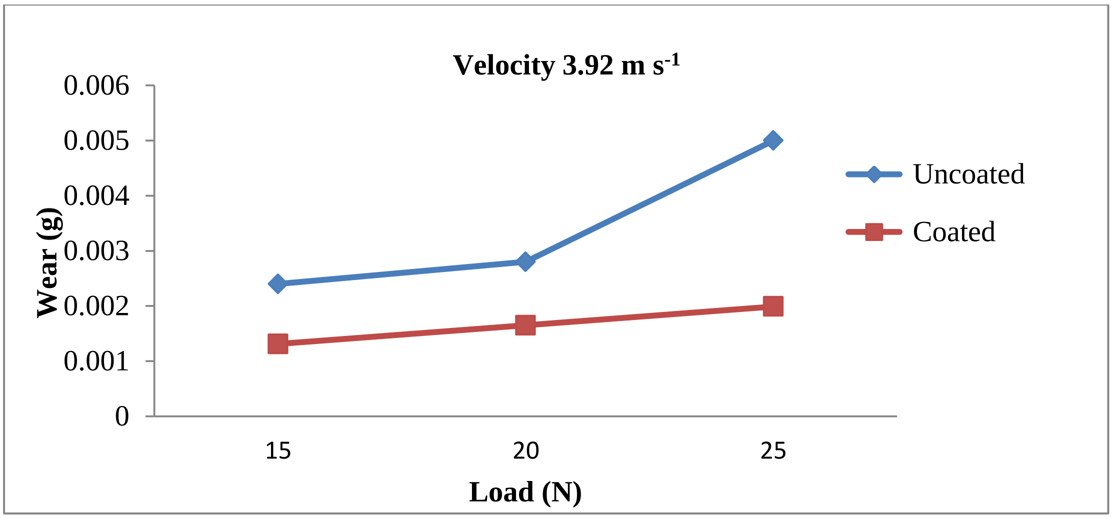


Fig. 4.3: Effect of load on wear at 3.92 m s^{-1} velocity

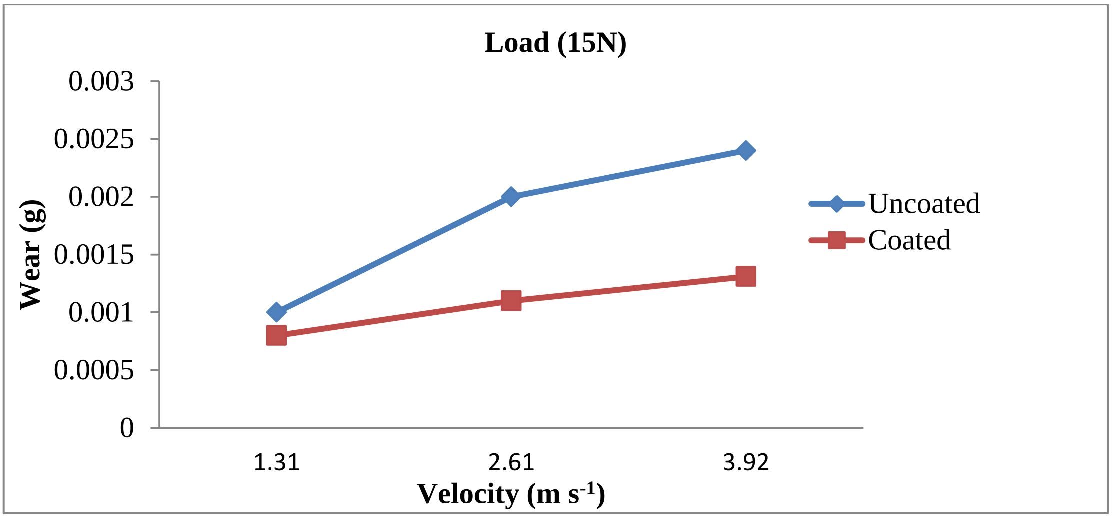


Fig. 4. 4: Effect of velocity on wear at constant 15 N load

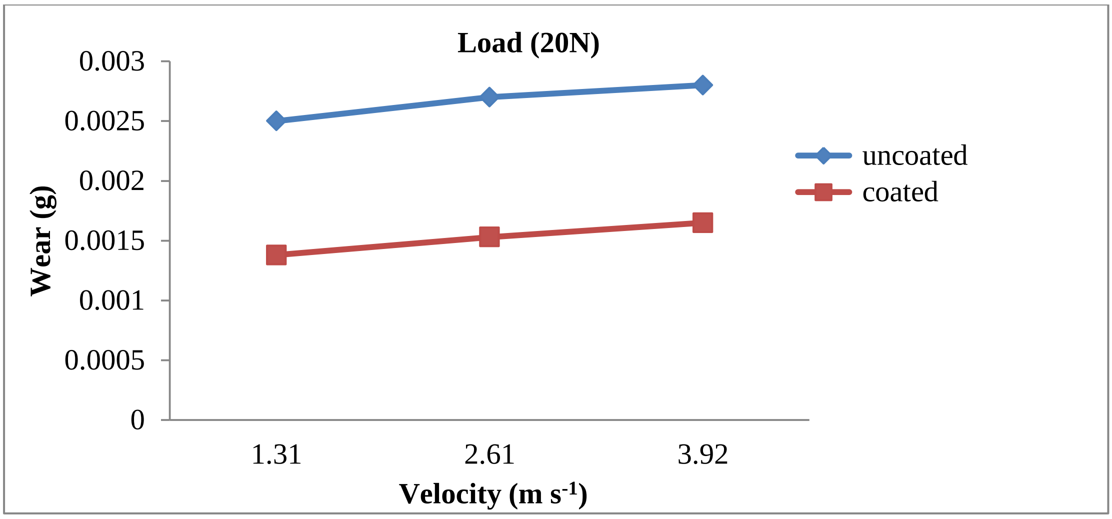


Fig. 4.5: Effect of velocity on wear at constant 20N load

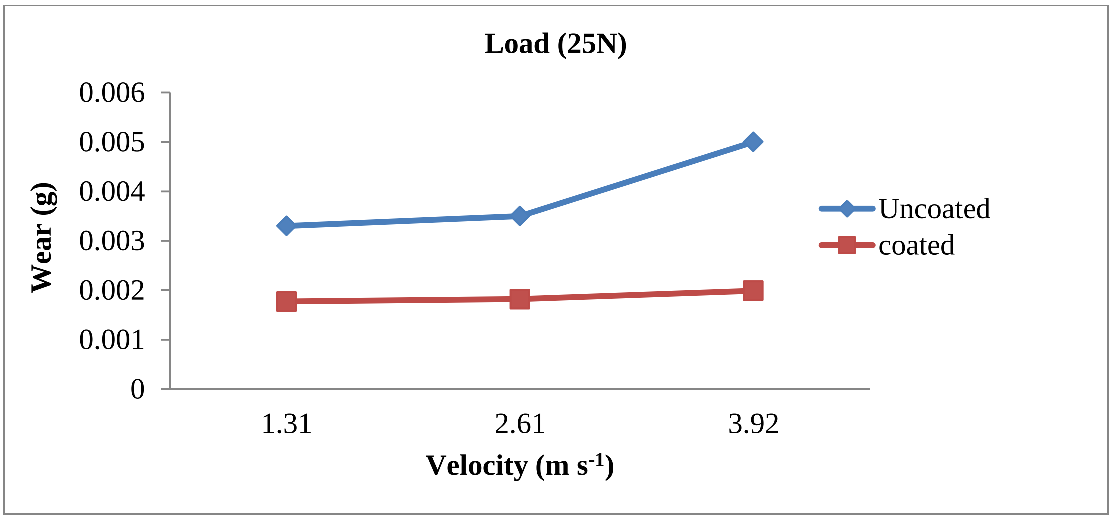


Fig. 4.6: Effect of velocity on wear at constant 25N load

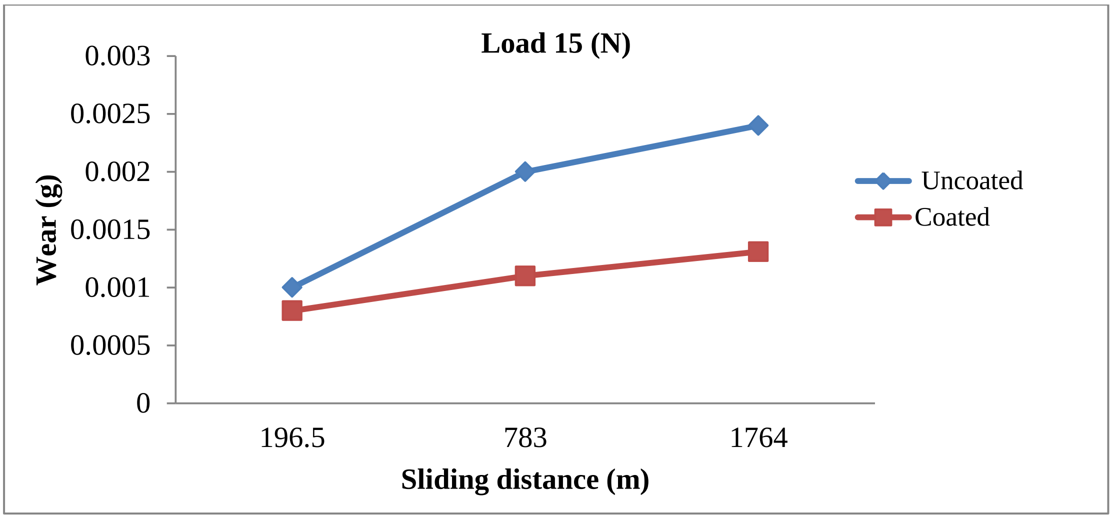


Fig. 4.7: Effect of sliding distance on wear at 15 N constant load

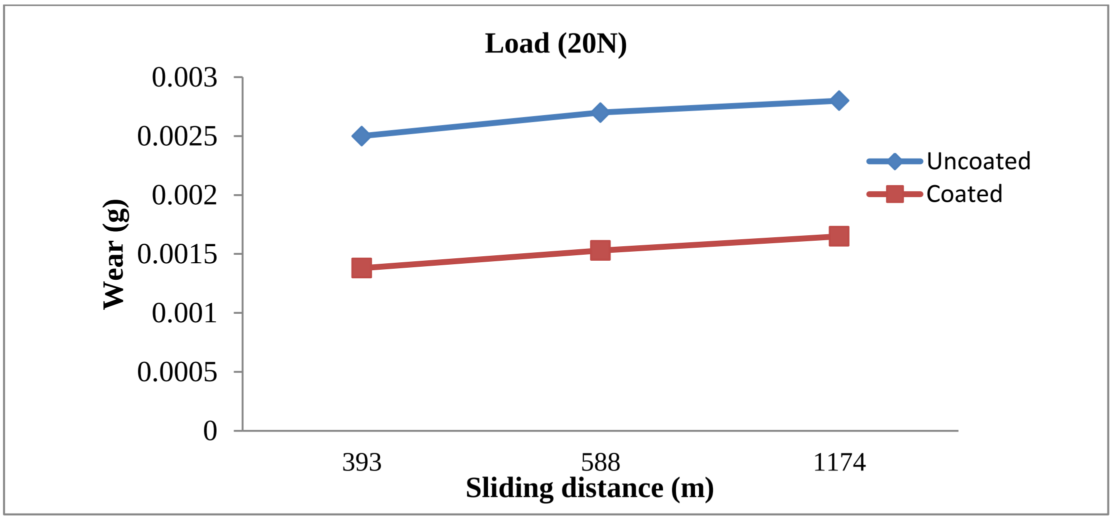


Fig. 4.8: Effect of sliding distance on wear at 20 N constant load

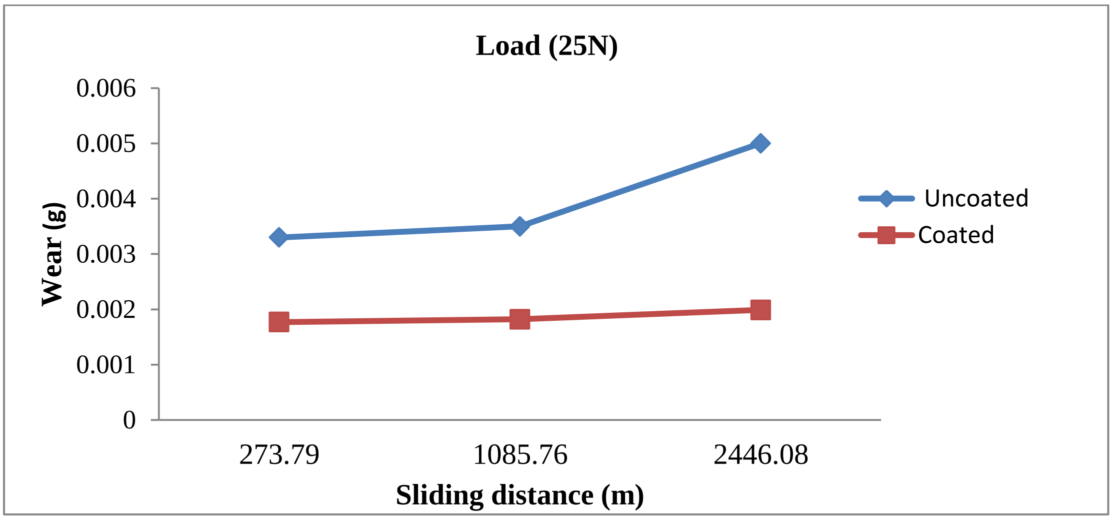


Fig. 4.9: Effect of sliding distance on wear at 25 N constant load

4.1.4 Specific wear rate

The specific wear rate was calculated and presented in Table 4.4 for uncoated and coated specimens. The table represents the value of specific wear rate of uncoated and coated specimens at variable load, sliding velocity, time and sliding distance.

Table 4.4 Specific wear rate of uncoated and coated specimen

Exp.No.	Load (N)	Sliding velocity ($m\ s^{-1}$)	Time (s)	Sliding distance (m)	Wear loss (g)		Specific wear rate × 10^{-7} ($mm^3\ Nm^{-1}$)	
					Uncoated	Coated	Uncoated	Coated
1	15	1.31	150	196.50	0.0010	0.00080	0.432192	0.030038
2	15	2.61	300	783.00	0.0020	0.00110	0.216924	0.016457
3	15	3.92	450	1764.00	0.0024	0.00131	0.115545	0.044156
4	20	1.31	300	393.00	0.0025	0.00138	0.405181	0.013817
5	20	2.61	450	1174.00	0.0027	0.00153	0.146486	0.076356
6	20	3.92	150	588.00	0.0028	0.00165	0.303306	0.024718
7	25	1.31	450	273.79	0.0033	0.00177	0.614167	0.015433
8	25	2.61	150	1085.76	0.0035	0.00182	0.164257	0.062932
9	25	3.92	300	2446.08	0.0050	0.00199	1.041570	0.015502

4.1.5 Coefficient of Friction (COF)

The Coefficient of friction plays an important role in determining the resistance behavior of surface against wear. The Fig. 4.10 to 4.18 represents the coefficient of friction from Exp. No. 1 to 9. The graphs shown in figures represent the relation between COF and time for coated and uncoated specimens.

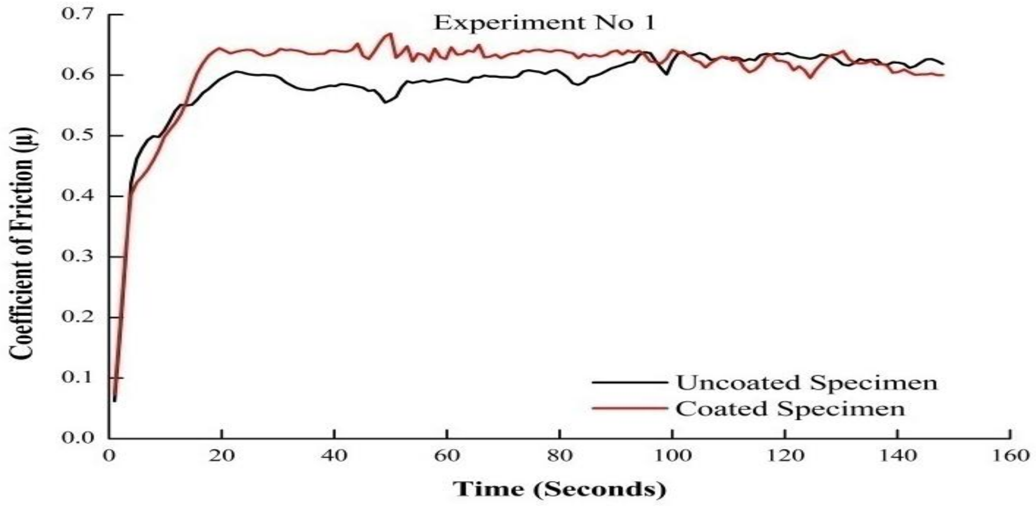


Fig. 4.10: COF for uncoated and coated specimen for 1st Experiment

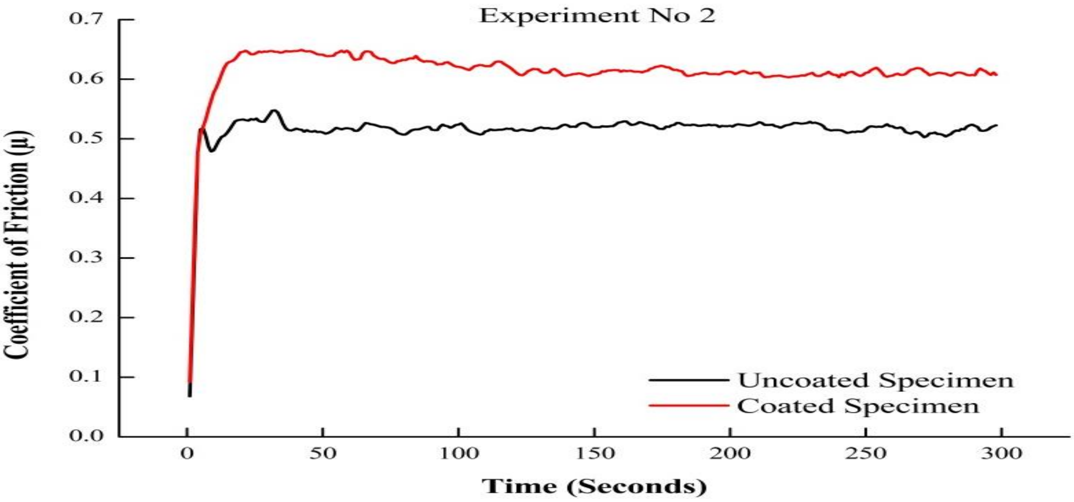


Fig. 4.11: COF for uncoated and coated specimen for 2nd Experiment

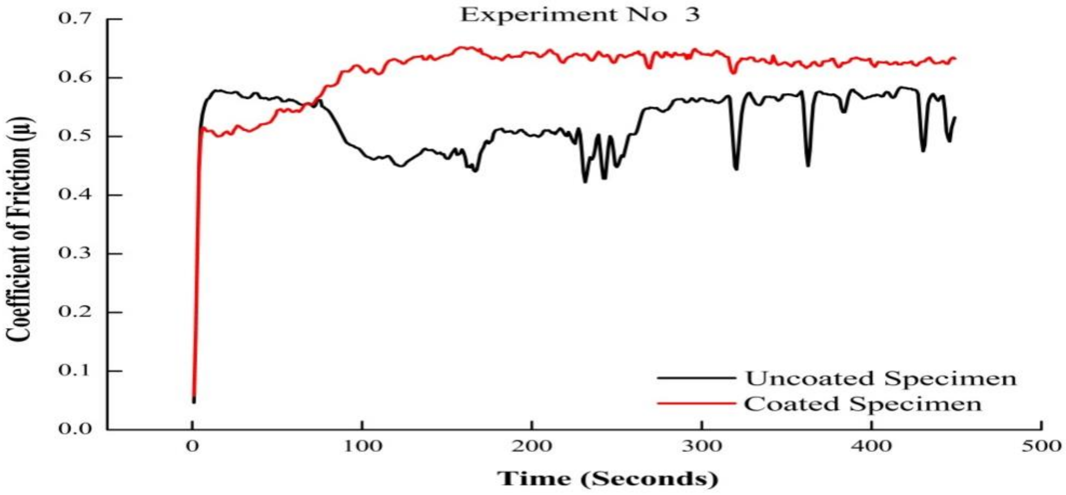


Fig. 4.12: COF for uncoated and coated specimen for 3rd Experiment

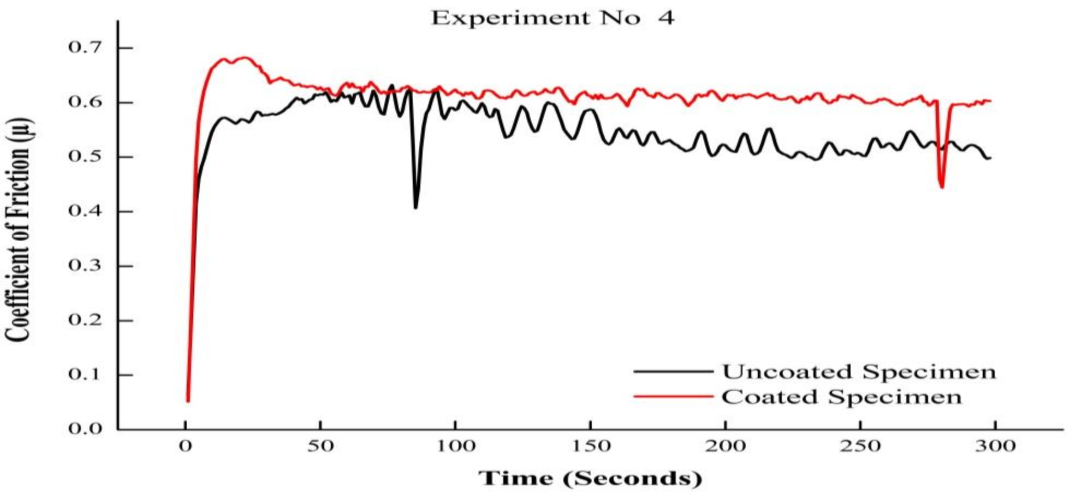


Fig. 4.13: COF for uncoated and coated specimen for 4th Experiment

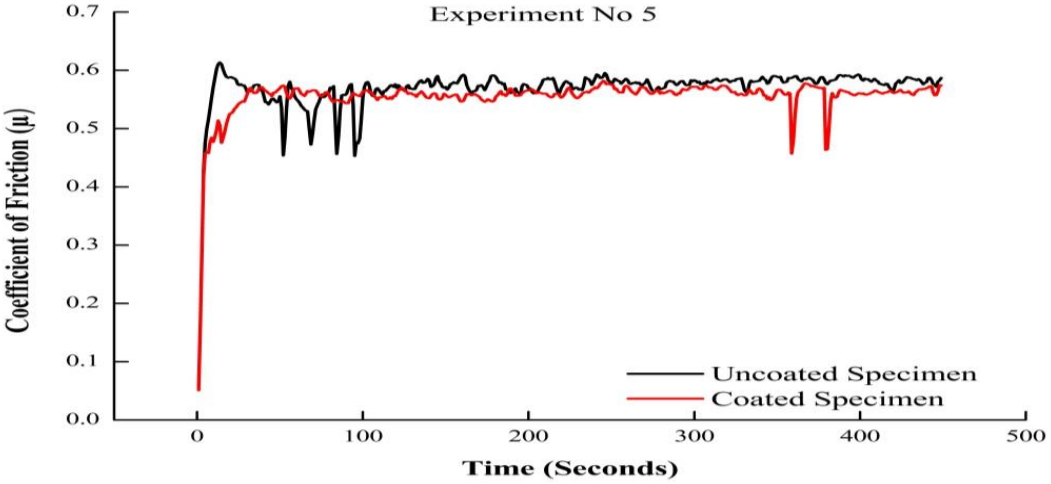


Fig. 4.14: COF for uncoated and coated specimen for 5th Experiment

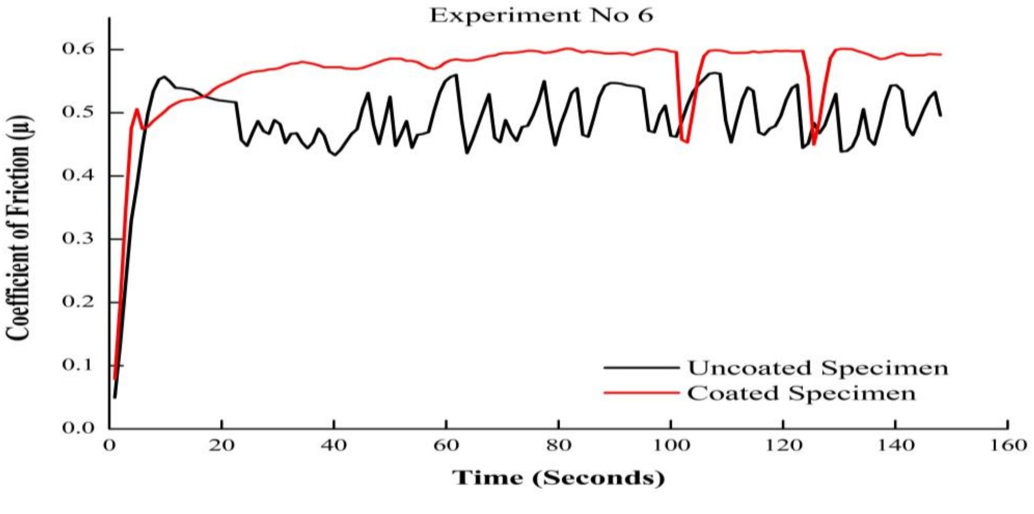


Fig. 4.15: COF for uncoated and coated specimen for 6th Experiment

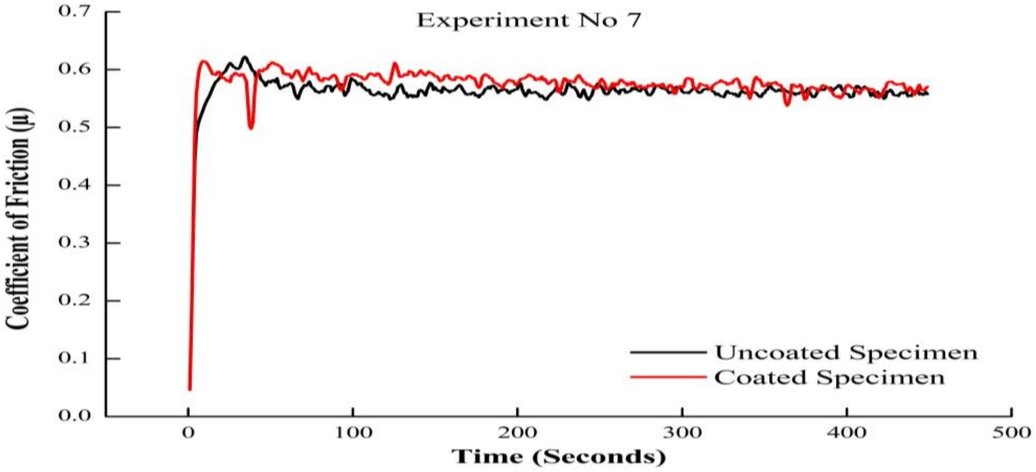


Fig. 4.16: COF for uncoated and coated specimen for 7th Experiment

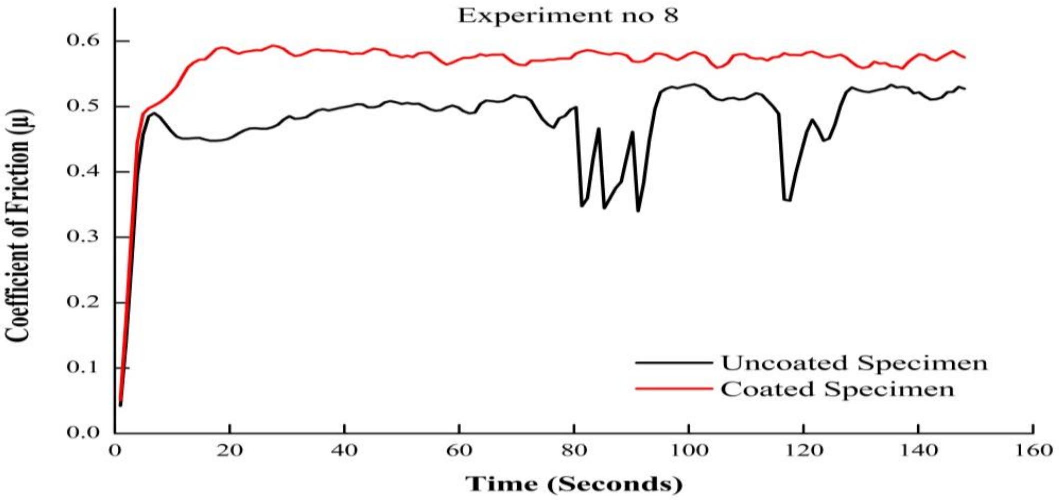


Fig. 4.17: COF for uncoated and coated specimen for 8th Experiment

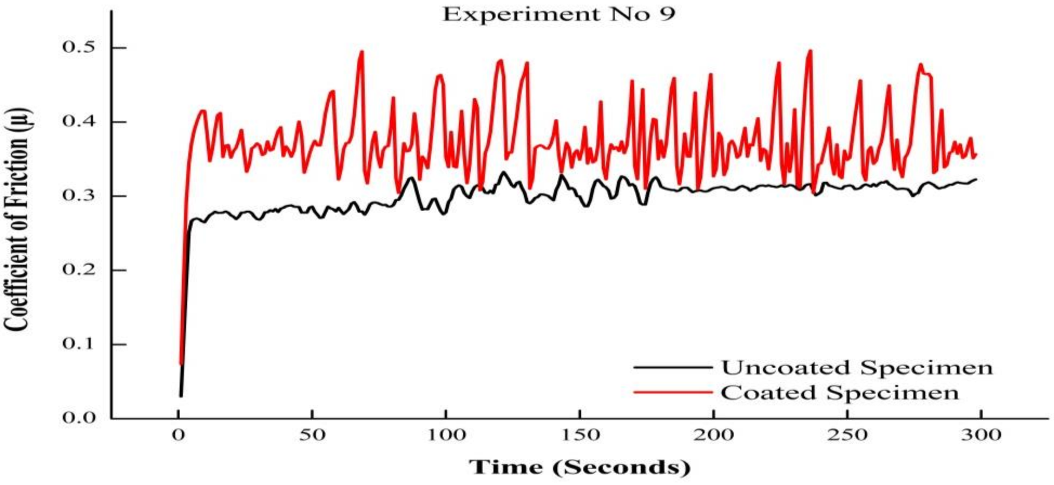


Fig. 4.18: COF for uncoated and coated specimen for 9th Experiment

4.1.6 Analysis of variance (ANOVA)

4.1.6.1 ANOVA for uncoated specimen

The analysis of variance (ANOVA) was used to identify that parameter which affects the wear loss significantly. The ANOVA for uncoated specimens is shown in Table 4.5. The percentage contribution of process parameters for wear loss was calculated and presented. The ANOVA indicates that wear loss for uncoated specimen is significantly affected by load (70%) followed by sliding velocity (20 %), and time (10%). The models summary (Table 4.6) showed that the model has 99.38% R^2 value which means model is significant. The residual plots for wear of uncoated specimens are shown in Fig. 4.19.

Table 4.5 ANOVA for uncoated specimen

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Load	2	0.000007	0.000003	115.11	0.009	70%
Sliding velocity	2	0.000002	0.000001	32.44	0.030	20%
Time	2	0.000001	0.000000	13.44	0.069	10%
Error	2	0.000000	0.000000			
Total	8	0.000010				

Table 4.6 Model Summary for ANOVA

S	R^2	R^2 (adj)	R^2 (pred)
0.0001732	99.38 %	97.53 %	87.50 %

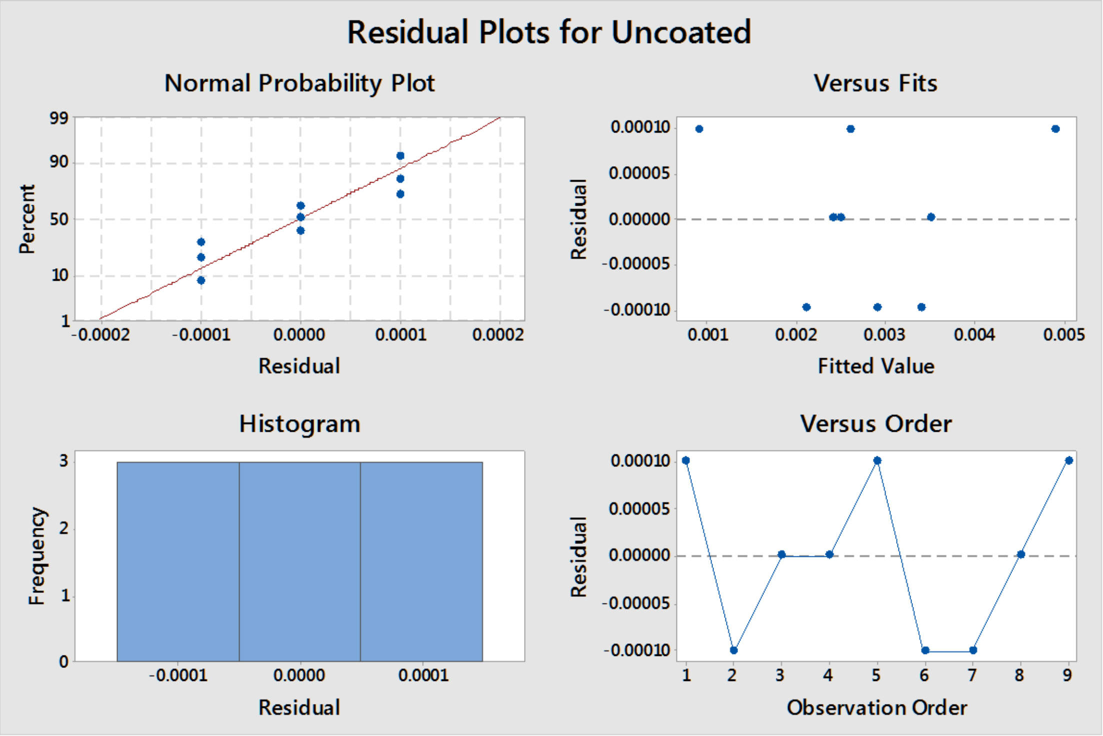
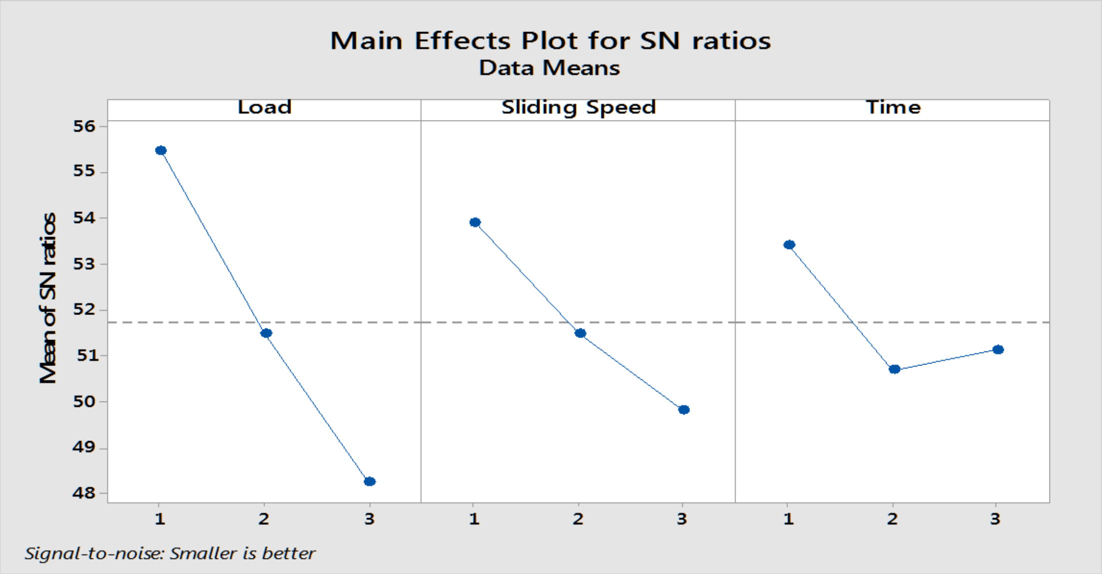


Fig. 4.19: Residual plots for uncoated specimen

4.1.6.2 S/N ratio and data means

The S/N ratio and data means plots are presented in Fig. 4.20 and Fig. 4.21, respectively. The graphs showed variation of individual parameters with respect to increase in the levels on wear behavior. Depending upon required response characteristics, three types of S/N ratio criteria are followed by researchers which are higher the better, nominal the better and lower the better. In the present test, lower the better S/N ratio criteria was chosen and calculated as per equation 4.1

$$\eta_{ij} = -10\log\{\frac{1}{n}\sum_{i=1}^{n} y_{ij}^{2}\} \tag{4.1}$$



Signal-to-noise: Smaller is better

Fig. 4.20: S/N ratio plots for uncoated specimen

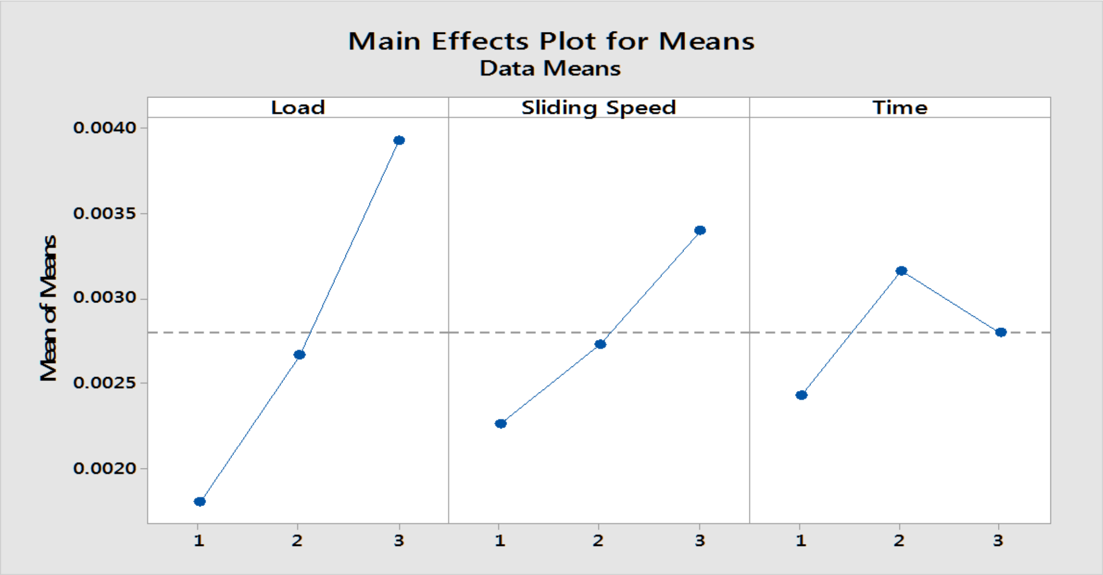


Fig. 4.21: Data means plots for uncoated specimen

4.1.6.3 Analysis of variance (ANOVA) for coated specimen

The ANOVA for coated specimen and the percentage contribution of process parameters for wear loss were calculated and presented in Table 4.7. The ANOVA indicates that wear loss for coated specimen is significantly affected by load (100%) as equated to other process parameters. The models summary (Table 4.8) showed that the model has 99.26 % R^2 value which means model is significant. The residual plots for wear of uncoated specimens are shown in Fig. 4.22.

Table 4.7 Analysis of variance for coated specimen

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Load	2	0.000001	0.000000	111.28	0.009	100%
Sliding velocity	2	0.000000	0.000000	19.69	0.048	--
Time	2	0.000000	0.000000	2.30	0.303	--
Error	2	0.000000	0.000000			
Total	8	0.000001				

Table 4.8 Model summary for ANOVA

S	R^2	R^2 (adj)	R^2 (pred)
0.0000651	99.26 %	97.02 %	84.92 %

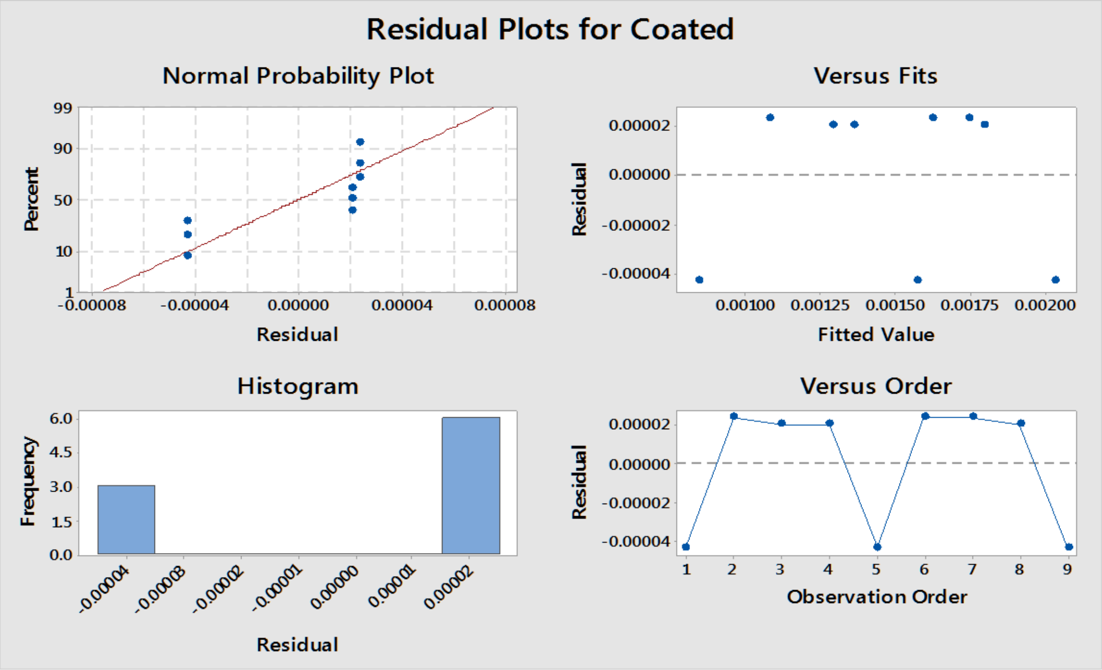


Fig. 4.22: Residual plots for coated specimen

4.1.6.4 S/N ratio and data means

The S/N ratio and data means plots are presented in Fig. 4.23 and Fig. 4.24, respectively. The graphs showed variation of individual parameters with respect to increase in the levels on wear behavior. In the present test, lower the better S/N ratio criteria was chosen and calculated as per equation 4.1.

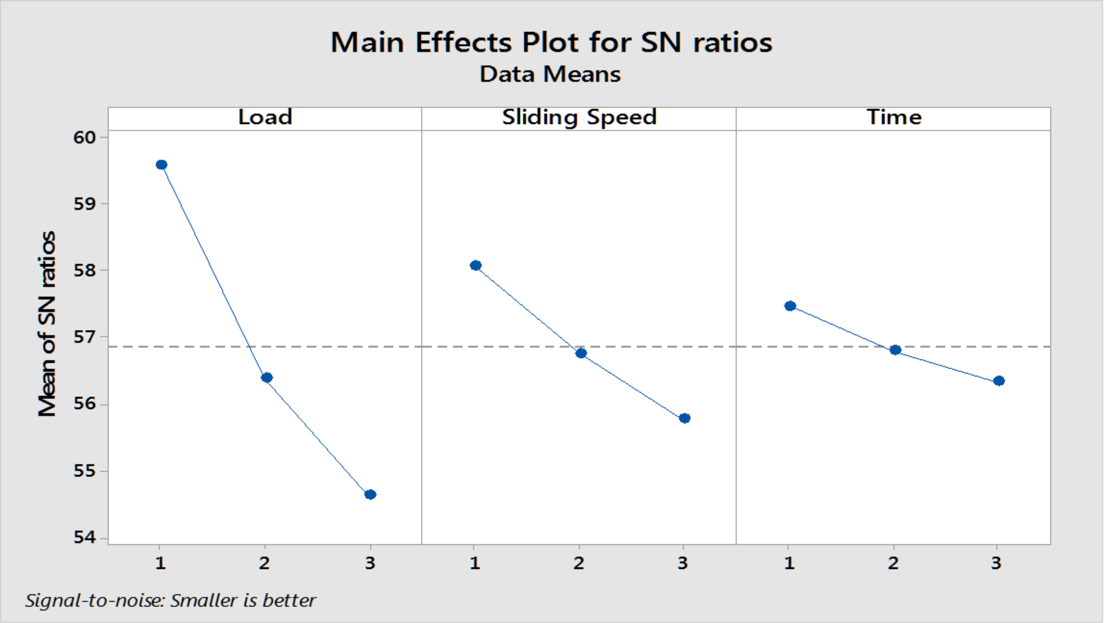


Fig. 4.23: S/N ratio plots for coated specimen

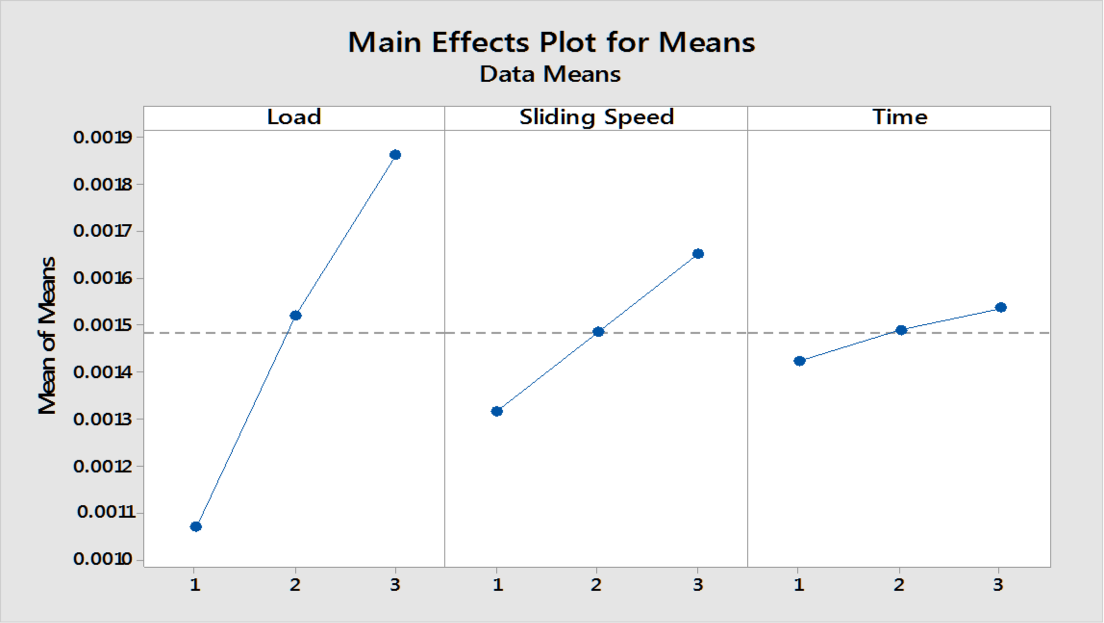


Fig. 4.24: Data means plots for coated specimen

4.2 Wear testing (Field)

The cutter bar blades (A type) and chopping cylinder blades (M type) made of high carbon steel was fixed in straw combine and operated with Massey Ferguson 9000 tractor at engine throttle setting corresponding to 1750 rpm for 38.33 hours for harvesting of wheat straw left over by grain combine. The wear of the blades were analyzed with respect to the weight of the blades and dimensions of the blades.

4.2.1 Wear analysis with respect to weight

4.2.1.1 Cutter bar (A type) blades

The wear losses in uncoated and coated cutter bar blades (A type) are presented in Table 4.9 and Fig. 4.25. The weight of uncoated blades reduced from 64.51 to 62.68 g, whereas, it reduced from 64.26 to 63.81 g in case of coated blades. The total weight loss in coated blades was 75.04 % lower than uncoated blades.

Table 4.9 Weight loss comparison in cutter bar blades (A type)

Sr. No.	Cutter bar blade	Weight (g)		Weight loss (g)	Change (%)
		Before	After		
1	Uncoated	64.51	62.68	1.83	75.04
2	Coated	64.26	63.81	0.45	

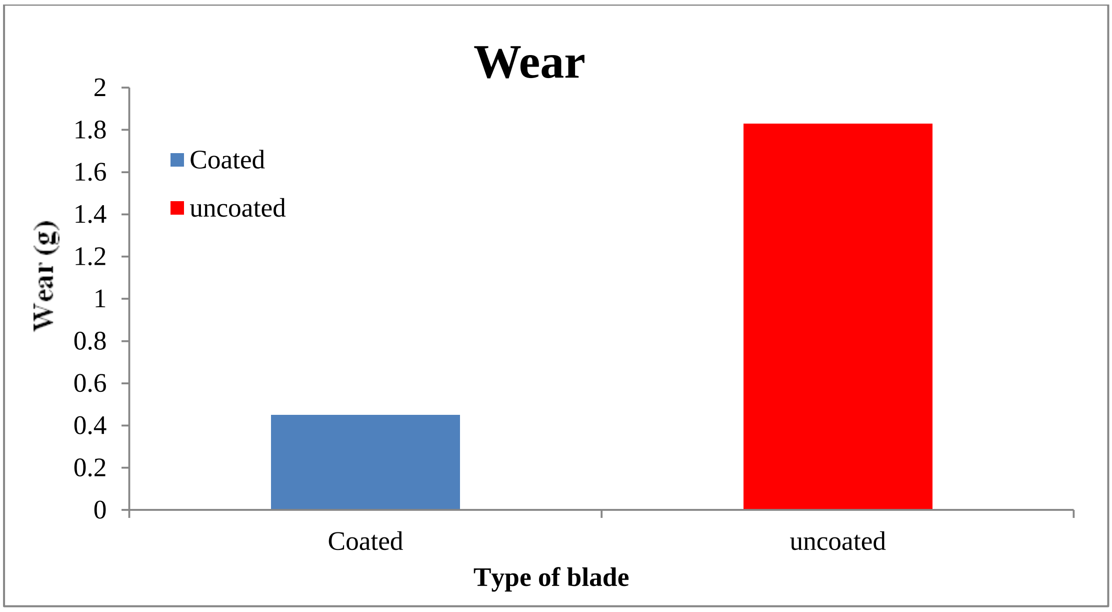


Fig. 4.25: Wear of coated and uncoated cutter bar (A type) blades with respect to weight loss

4.2.1.2 Chopping cylinder (M type) blades

The wear losses in uncoated and coated chopping cylinder blades (M type) are presented in Table 4.10 and Fig. 4.26. The weight of uncoated blades reduced from 70.30 to 69.26 g, whereas, it reduced from 70.12 to 69.82 g in case of coated blades. The total weight loss in coated blades was 71.15 % lower than uncoated blades of chopping cylinder.

Table 4.10 Weight loss comparison in chopping cylinder blades (M type)

Sr. No.	Chopping cylinder blade	Weight (g)		Weight loss (g)	Change (%)
		Before	After		
1	Uncoated	70.30	69.26	1.04	71.15
2	Coated	70.12	69.82	0.30	

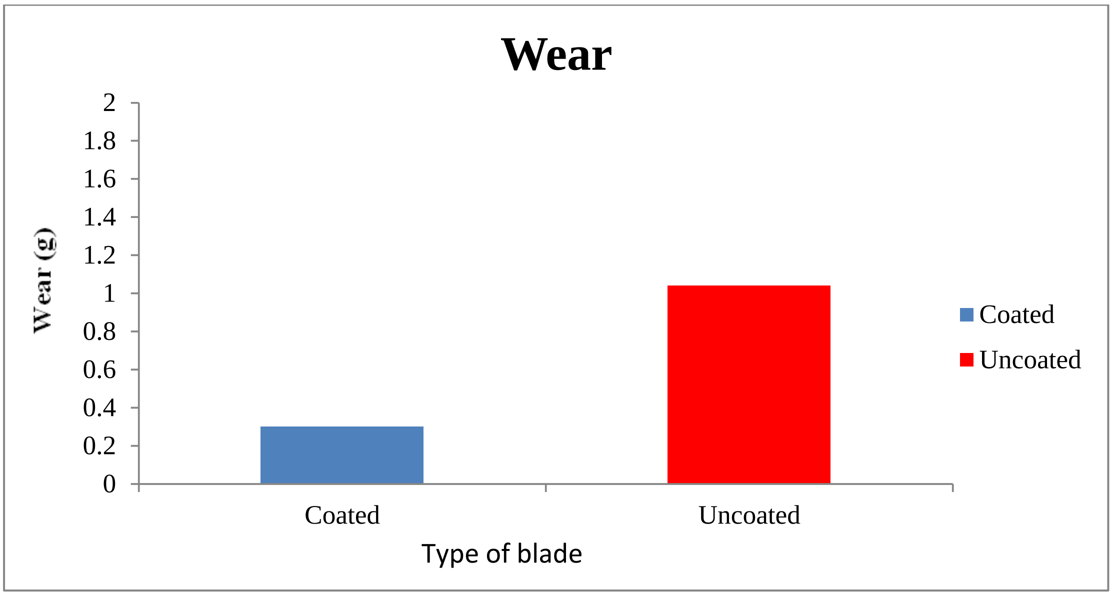


Fig. 4.26: Wear of coated and uncoated cylinder (M type) blades with respect to weight loss

4.2.2 Wear analysis with respect to the dimensions of the blades

4.2.2.1 Cutter bar blades (A type)

The wear of coated and uncoated blades were observed with respect to total length of blade, width at the tip of blade and width at 30 mm below the tip of blade with the help of digital vernier caliper. The results are presented in Table 4.11 and Fig. 4.27. The change in dimension of uncoated cutter bar blades with respect to total length of blade, width at tip of blade and width at point below 30 mm from the tip of blade was 0.446, 14.400 and 6.190 %, respectively, whereas, in case of cryogenic coated cutter bar blades, it was 0.350, 10.02 and 4.48 %, respectively. Due to cryogenic treatment, the cutter bar blade (A type) resulted in less reduction in dimension. The comparative analysis showed that the dimension reduction in coated blades with respect to total length of blade, width at tip of blade and width at point below 30 mm from the tip of blade were 20, 27.39 and 30.40 % less as compared to uncoated blades.

Table 4.11 Improvement in wear (%) of A type blades (dimensions basis)

Sr. No.	Dimension	Change in dimension (%)		Improvement (%)
		Uncoated	Coated	
1	Length	00.446	00.350	20.00 %
2	Width at the tip	14.400	10.020	27.39 %
3	Width at 30 mm from tip	06.190	04.480	30.40 %

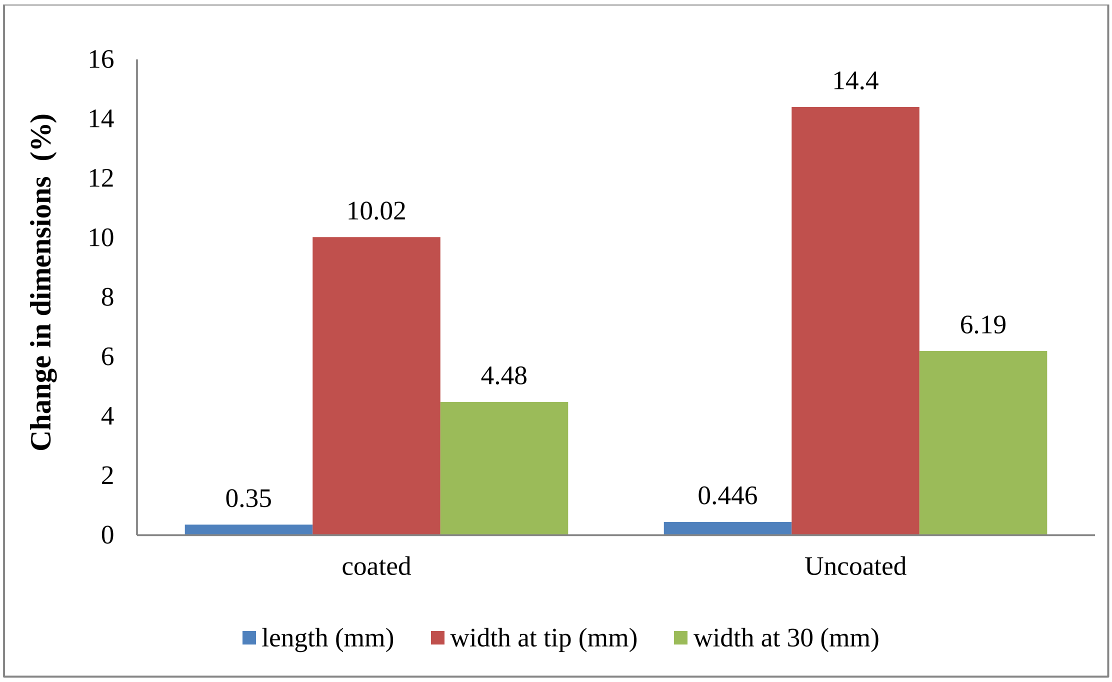


Fig. 4.27: Wear of coated and uncoated cutter bar (A-type) blades with respect to dimensions

4.2.2.1 Chopping cylinder blades (M Type)

The wear of coated and uncoated chopping cylinder blades were observed with respect to total length of blade, width at the tip of blade and width at 30 mm below the tip of blade with the help of digital vernier caliper. The results are presented in Table 4.12 and Fig. 4.28. The change in dimension of uncoated blades with respect to total length of blade, width at tip of blade and width at point below 30 mm from the tip of blade was 1.086, 4.708 and 4.258 %, respectively, whereas, in case of cryogenic coated cutter bar blades, it was 0.908, 3.226 and 3.132 %, respectively. Due to cryogenic treatment, the chopping cylinder blade (M type) resulted in less reduction in dimension. The comparative analysis showed that the dimension reduction in coated blades with respect to total length of blade, width at tip of blade and width at point below 30 mm from the tip of blade were 16.39, 26.44 and 31.48 % less as compared to uncoated blades.

Table 4.12 Improvement in wear (%) of M type blades (dimensions basis)

Sr. No.	Dimension	Change in dimension (%)		Improvement (%)
		Uncoated	Coated	
1	Length	1.086	0.908	16.39 %
2	Width at the tip	4.708	3.226	26.44 %
3	Width at 30 mm from tip	4.258	3.132	31.48 %

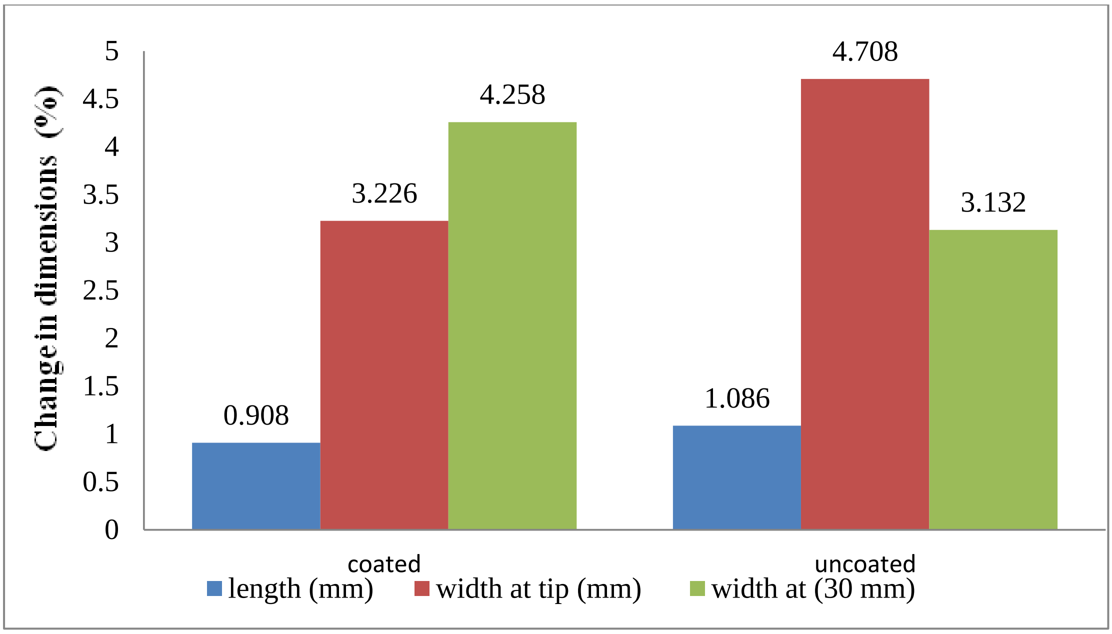


Fig. 4.28: Wear of coated and uncoated chopping cylinder (M-type) blades with respect to dimensions

4.3 Field Emission Scanning Electron Microscopy (FE-SEM)

The scanning electron microscope was used to generate SEM images to study the behavior of specimen surface during wear. Both of the specimens were scanned and checked at 100X magnification level. The SEM of uncoated and coated specimen is shown in Fig. 4.29 and Fig. 4.30, respectively.

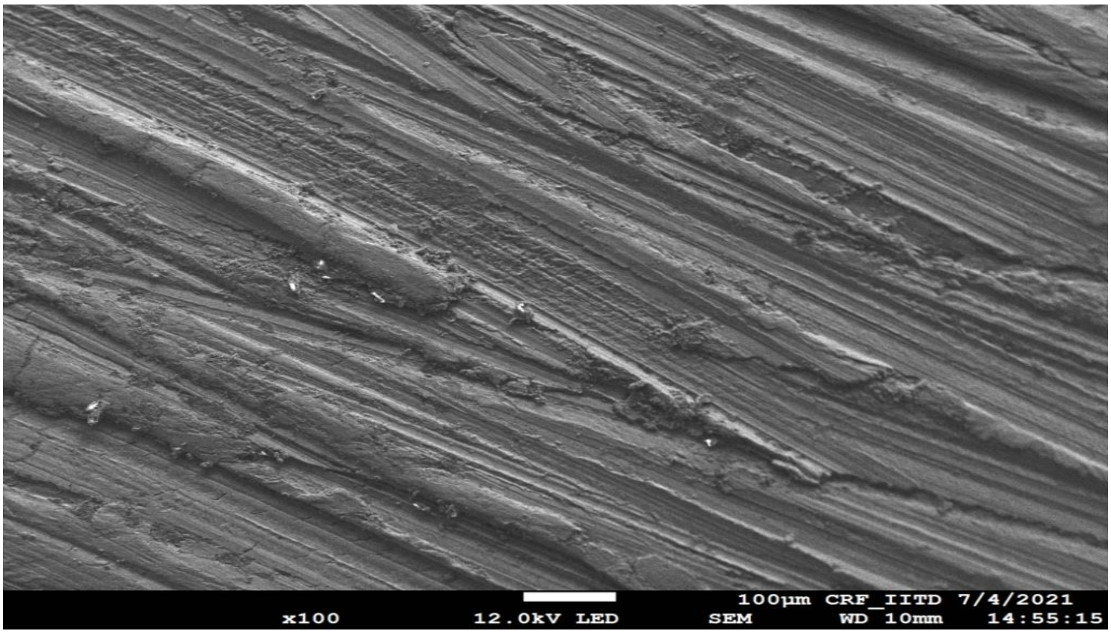


Fig. 4.29: FE-SEM of uncoated specimen

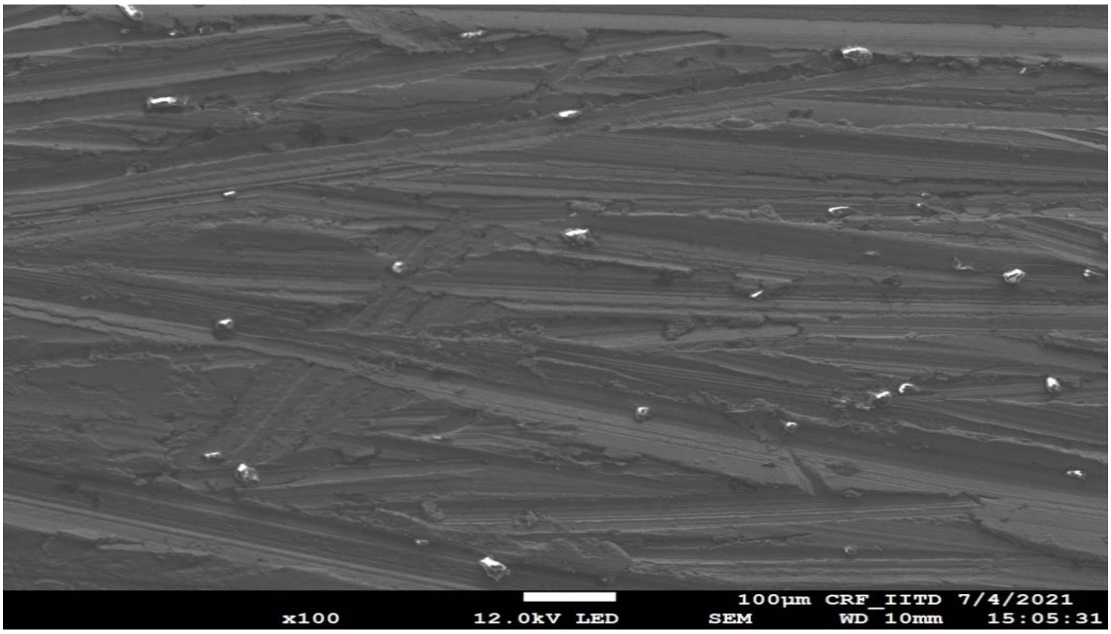
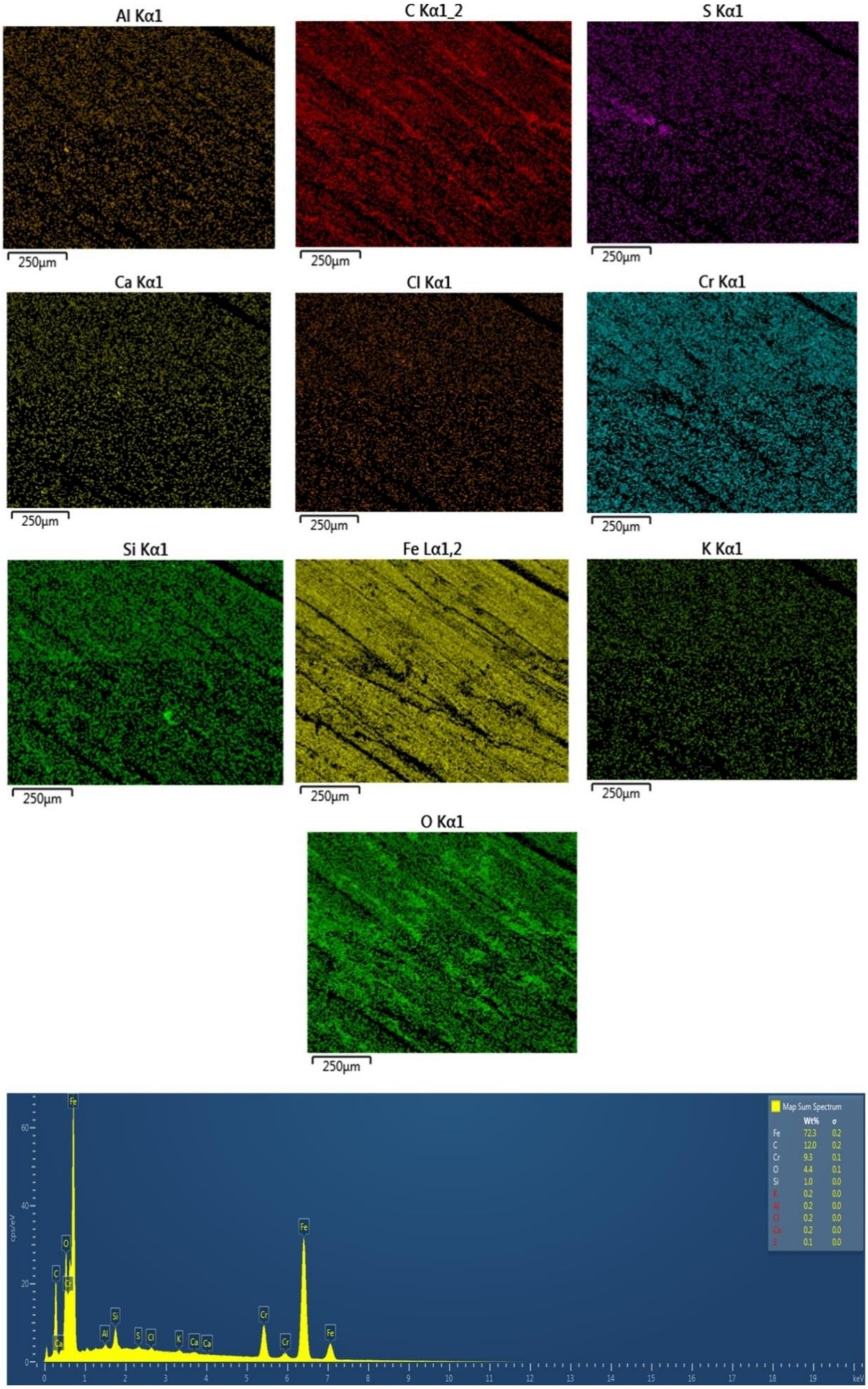


Fig. 4.30: FE-SEM of coated specimen

4.3.1 Energy Dispersive Spectroscopy

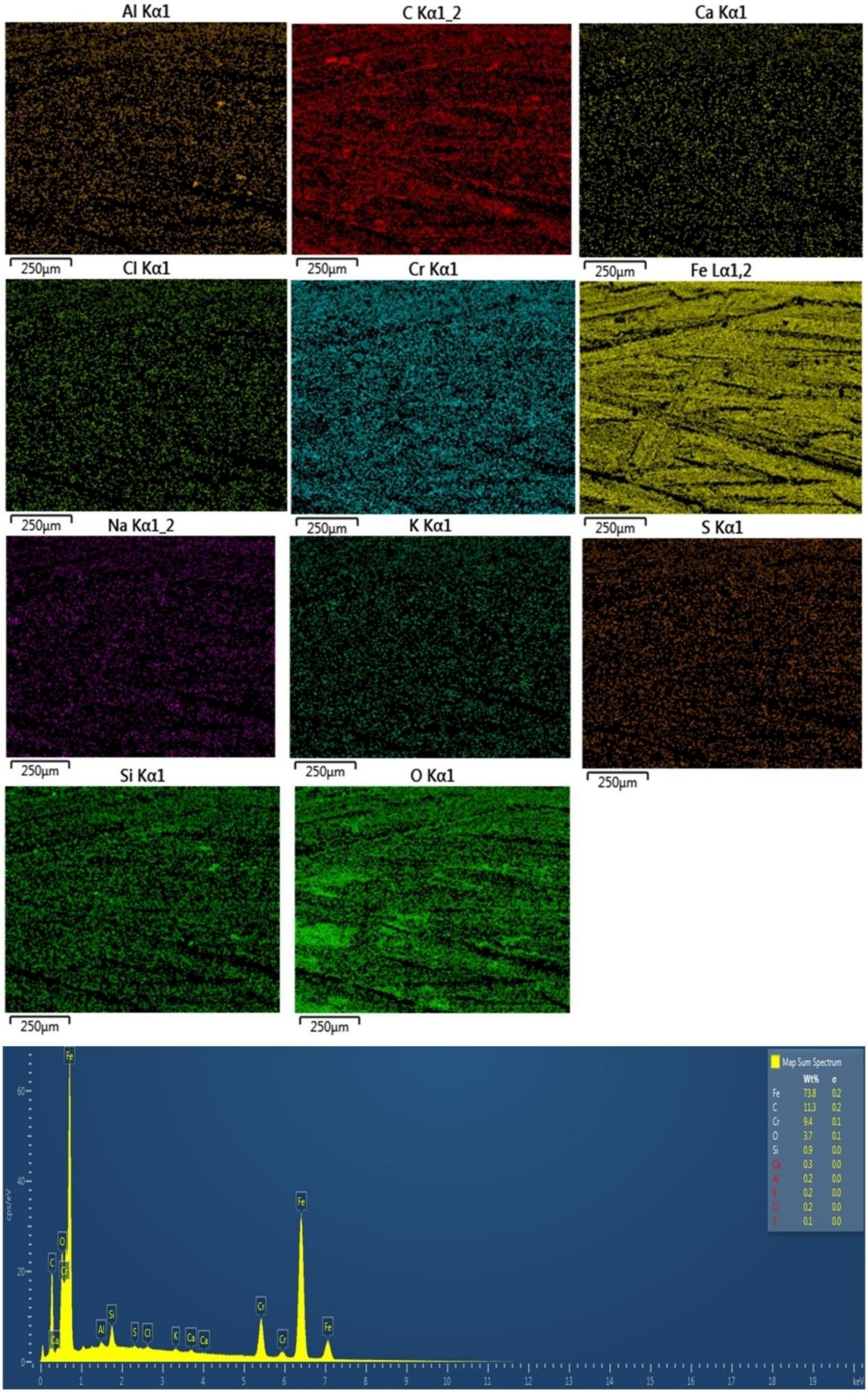
The Energy Dispersive Spectroscopy (EDS) was performed using Field Emission Scanning Electron Microscope. The EDS was performed to obtain the composition of the elements and newly constituted elements after cryogenic treatment. The EDS analysis of uncoated and coated specimen is shown in Fig. 4.31 and Fig. 4.32, respectively.



Map Sum Spectrum

	Wt%	σ
Fe	72.3	0.2
C	12.0	0.2
Cr	9.3	0.1
O	4.4	0.1
Si	1.0	0.0
K	0.2	0.0
Al	0.2	0.0
Cl	0.2	0.0
Ca	0.2	0.0
S	0.1	0.0

Fig. 4.31: EDS analysis of uncoated specimen



	Wt%	σ
Fe	73.8	0.2
C	11.3	0.2
Cr	9.4	0.1
O	3.7	0.1
Si	0.9	0.0
Ca	0.3	0.0
Al	0.2	0.0
K	0.2	0.0
Cl	0.2	0.0
S	0.1	0.0

Fig. 4.32: EDS analysis of coated specimen

4.4 Economic analysis

4.4.1 Cost of blade before treatment

The initial cost of cutter bar blade (A type) and chopping cylinder blade (M type) was Rs. 24 and Rs. 18, respectively. The blades were manufactured by Marshal Company and purchased from Shiv Narain & Sons., Automobile market, Hisar.

4.4.2 Cost of cryogenic treatment per blade

The cost of cryogenic treatment was calculated with respect to the batch. The capacity of machine in terms of weight per batch was 260 kg. The cost of cryogenic coating for one batch was Rs. 9000. The average weight of one cutter bar blade (A type) was 65 g, therefore 4000 number of can be coated in one time. The average weight of the chopping cylinder blade (M type) was 71 g, therefore 3600 blades can be coated per batch. The cost of the cryogenic treatment was Rs 2.25 and Rs.2.50 for cutter bar blade (A type) and chopping cylinder blade (M type), respectively (Table 4.13 and 4.14).

Table 4.13 Cost analysis of cryogenic treatment per blade of cutter bar blade (A type)

S. No.	Particulars	Values
1	Cost of blade, Rs	24
2	No. of blade in cutter bar	30
3	Weight of one blade, g	65
4	Number of blades to be cryogenic treated in one lot	4000
5	Additional cost for proposed cryogenic treatment on one lot, Rs	9000
6	Additional cost per blade, Rs	2.25
7	Percentage increase in cost per blade due to cryogenic treatment, %	9.38
8	Percentage improvement in wear rate resistance of blade after cryogenic treatment as compared to un-coated in field condition, %	75.04
9	Life of blade before treatment , h	400
10	Life of blade after treatment , h	700
11	Percentage increase in the life of blade due to cryogenic treatment, %	75
12	Cost of a blade per hour before the cryogenic treatment, Rs	0.06
13	Cost of a blade per hour after cryogenic treatment, Rs	0.03

Table 4.14 Cost analysis of cryogenic treatment per blade of chopping cylinder blade (M type)

S. No.	Particulars	Values
1	Cost of blade, Rs	18
2	No. of blade in chopping cylinder blade	304
3	Weight of one blade, g	71
4	Number of blades to be cryogenic treated in one lot	3600
5	Additional cost for proposed cryogenic treatment on one lot, Rs	9000
6	Additional cost per blade, Rs	2.50
7	Percentage increase in cost per blade due to cryogenic treatment, %	13.61
8	Percentage improvement in wear rate resistance of blade after cryogenic treatment as compared to un-coated in field condition, %	71.15
9	Life of blade before treatment , h	150
10	Life of blade after treatment , h	256
11	Percentage increase in the life of blade due to cryogenic treatment ,%	70
12	Cost of a blade per hour before the cryogenic treatment, Rs	0.12
13	Cost of a blade per hour after cryogenic treatment, Rs	0.08

4.4.3 Percentage increase in cost of blade due to cryogenic treatment

The percentage increase in cost of cutter bar and chopping cylinder blades due to cryogenic treatment was 9.38 and 13.61 %, respectively The economic analysis clearly justified the additional cost of cryogenic treatment. The cost of cutter bar and chopping cylinder blades per hour after the treatment were decreased by 50 and 33.3%, respectively (Table 4.13 and 4.14).

CHAPTER-V

DISCUSSION

The results of the investigation entitled "Effect of cryogenic treatment on the performance of straw combine blade" obtained from laboratory and field experiments were discussed in this chapter under following headings:

5.1 Cryogenic parameters
5.2 Wear testing (Pin on disc test setup)
5.3 Field experiments
5.4 Metallurgical investigation
5.5 Economic analysis

5.1 Cryogenic parameters

The deep cryogenic treatment was performed with parameters, *i.e.* soaking temperature (-190°C), cooling rate (1^{o} min^{-1}), soaking period (16 h) and heating rate (1°C) instead of general cryogenic treatment because previous studies conducted by Li *et al*., 2016 and Thornton *et al*., 2014 showed that there was a more micro-structural improvement in the materials which were deep cryogenic treated as compared to general cryogenic treated materials. Similarly, Gill *et. al*., 2011 concluded that cutting life of tungsten carbide inserts increased by 27% in shallow cryogenic treatment and 37% in case of deep cryogenic treatment.

5.2 Wear testing (Pin on disc test setup)

5.2.1 Effect of load, sliding velocity and time on the wear

The wear of uncoated and coated high carbon steel specimen increased from 0.0010 to 0.0050 g and 0.00080 to 0.00199 g, respectively with increase in value of load and sliding velocity. Ameen *et al.,* 2011 presented similar results and concluded that adhesive wear is directly proportional to time, sliding velocity, sliding distance, load, and time. Kumar *et al.*, 2016 concluded that as the sliding distance increased, the wear resistance increased from 20 to 60 % with applied load and sliding velocity. The variation with respect to testing parameters in dry sliding wear for the uncoated specimen is shown in Fig. 4.21. The trends shown for the wear loss with variation in load depicts that the wear loss increased with the increase in load or the resistance of specimen against wear decreased with an increase in applied load. When the applied load changes from 15 to 20 N, a significant increase in wear loss was observed, but when the load goes from 20 to 25 N, the growth in wear loss was much faster. It seems that at a higher load, the surface starts degrading at a higher rate due to molecular debonding. The plotted results for the effect of variation in sliding velocity on wear loss reveal almost similar trends observed for the applied load. When the sliding velocity varied from 1.31 to 2.61 m s^{-1}, the increase in wear loss is observed at a lower rate. With further increase in sliding velocity *i.e.* from 2.61 to 3.92 m s^{-1}, a steep increase in wear loss was observed. Because of higher sliding velocity, the surface abraded quickly, and inner grains directly contact the abrasive surface. The available results for the time showed that the wear increased with time initially but at the next level decreased with time. The variation with respect to testing parameters in dry sliding wear for the coated specimen is shown in Fig. 4.24. The trends shown in the graph for wear loss depict somehow similar trend for the parameters of uncoated specimen. However, the graphs show uniformity in wear loss of coated specimen as compared with the uncoated specimen. There is no unpredicted and surprising increase in wear with increase in the values of parameters. The coating helped in showing uniform resistance against wear. The signal to noise (S/N) ratio graph showed that if the blade is operated at initial levels, *i.e.* load at 15 N, sliding velocity (1.31 m s^{-1}) and time (150 sec), there will be less wear and life of the blades be higher. The analysis on the coefficient of friction on both the specimens showed that coated specimen has high coefficient of friction in entire experimental conditions. It is because of the cryogenic treatment effect as the surface become harder and showed brittle properties. Due to which the surface's hard asperity showed more resistance and high coefficient of friction.

5.3 Field Experiments

5.3.1 Wear with respect to weight

In the present study, the wear of the cutter bar blade (A type) and chopping cylinder blade (M type) were analyzed. The average % wear (concerning weight loss of blades) of the uncoated and coated blades of cutter bar were found to be 1.83 and 0.45 g, respectively. Therefore, an improvement in wear resistance of the coated cutter bar blades was 75.04 % compared to uncoated cutter bar blades. Similarly, the average percentage of wear in chopping cylinder blades for uncoated and coated specimens was 1.04 and 0.30 g, respectively. Therefore, there was a 71.15 % improvement in wear resistance of coated chopping cylinder blades concerning the uncoated blades (Table 4.12). Singh *et al.*, 2020 reported that abrasive wear loss in cryogenically treated specimens was reduced by 60% and that the hardness of the specimens was increased by 206.73 % as compared to untreated specimens. Jagtar *et al.*, 2001 studied the effect of deep cryogenic treatment and concluded that there was about 70 % increase in the wear resistance due to the cryogenic treatment.

5.3.2 Wear with respect to dimensions

The average wear percentages of the uncoated and coated cutter bar blade (A type) concerning the dimensions were found to be 0.446, 14.400, 6.190 and 0.350, 10.020, 4.480 (%) for total length, width at tip of the blade and width at 30 mm down from the tip of the blade respectively. Similarly, for the chopping cylinder blades (M type), the average wear percentages of the uncoated and coated blades concerning total length, width at tip and width at 30 mm down from the tip of the blades was 1.086, 4.708, 4.258 and 0.908, 3.226, 3.132 (%), respectively (Table 4.12 and Table 4.13). The comparative analysis showed that uncoated blades for both cutter bar and chopping cylinder exhibits more wear percentage than coated blades. Nutu *et. al.*, 2017 conducted experiment to determine the wear resistance of devices used for cutting the stalks of agricultural plants and concluded that there was 2.498 % wear after 100 hours of operation.

5.4 Metallurgical investigation

5.4.1 Field Emission Scanning Electron Microscope

Scanning Electron Microscopy was used for the metallurgical investigation of the uncoated and coated specimens. From the SEM, it is evident that the uncoated surface has deeper grooves than the coated sample. Chang 2005 studied the rolling or sliding wear performance of high silicon carbide-free bainitic steels. The results indicated that harder materials exhibited lower wear rates and the surface of the harder materials was very smooth surface due to their hardness.

5.4.2 Energy Dispersive Spectroscope (EDS)

An Energy-Dispersive Spectroscope was used to identify the elemental composition of the specimens before and after the cryogenic treatment. The analysis showed that there is little composition change in the coated specimens as compared to the uncoated specimens. Due to this elemental composition, there was an improvement in the grain structure of the coated specimens, and their intermolecular bonding also increased due to the cryogenic treatment. With this improvement in the grain structure and intermolecular forces, the wear resistance of the coated specimens also increased. Koneshlon *et al.,* 2011 studied the effect of cryogenic treatment on microstructure mechanical and wear behavior of the specimens and concluded an improvement in the wear resistance of the cryogenically treated specimens due to the uniform distribution of carbide grains.

5.5 Economic analysis

The cryogenic treatment resulted in increase of Rs. 2.25 cost per cutter bar blade (A type) and Rs. 2.50 cost per blade of chopping cylinder (M type). It increased the cost of cutter bar blade (A type) and chopping cylinder blade (M type) by 9.38 and 13.61 %, respectively. The increased cost of the blades was completely compensated due to the increase in the life of the blades by 75 and 70 % for cutter bar and chopping cylinder blades, respectively. Singh *et al.,* 2020 concluded that there was a 15.12 % increase in the cost of the specimens due to the cryogenic treatment. Molinari *et al.,* 2001 carried out a study of the effect of deep cryogenic treatment on the mechanical properties of tool steel and concluded that there was 50 % cost reduction due to cryogenic treatment. Lal *et al.,* 2000 observed that tin coating with the cryogenic treatment provided 45 % extended tool life.

CHAPTER-VI

SUMMARY AND CONCLUSION

Developed countries worldwide use automatic combine harvesters to harvest grain and straw combines for threshing the stalks left behind after harvesting wheat crops. The harvesting machines (combine, reaper and straw combine) are developed to overcome the shortage of labour and timely operations and facilitate the multi-cropping sequence in India. The cutting and chopping blades of the straw combine are generally made up of high carbon steel having 0.60 to 1.00 % carbon content. Carbon is the primary alloy for the higher strength and hardness of cutting steel blades. However, during cutting at high temperatures and in an abrasive environment, these cutting materials face excessive surface degradation, which ultimately reduces the blade's life and increases the cutting cost of the machine.

To overcome these limitations of high carbon steel blades or other cutting alloy blades, the cryogenic (shallow and deep) treatment has emerged as a popular surface treatment method for improving the surface properties of materials. Several researchers have worked on the performance evaluation of the materials after cryogenic treatment. Akincioglu *et al*., 2015 concluded that the life of the cutting tool increased by 27 % and the main cutting wear decreased by 11% with deep cryogenic treatment. Similarly, Singh *et al*., 2020 studied the abrasive wear behaviour of cryogenically treated boron steel used for rotavator blades and concluded that the hardness of cryo-treated specimen improved by 260.73 % and abrasive wear reduced by 60 % as compared to untreated material. Akincioglu *et al*.2015 concluded that as a result of cryogenic treatment, cutting forces decreased and surface roughness improved in parallel with improvements in the wear resistance of cutting tools. The deep cryogenic treatment had better results as compared to shallow cryogenic treatment. Gill *et al*., 2011 concluded that the cutting life of tungsten carbide inserts increased by 27 % in shallow cryogenic treatment and 37 % in the case of deep cryogenic treatment.

Keeping in view the possibility of performance improvement of high carbon steels (HCS) and the benefits of deep cryogenic treatment (DCT) on the work piece, the present research work **"Effect of cryogenic treatment on the performance of straw combine blade''** was undertaken with the following objectives:

1. To carry out wear analysis of cryogenic coated and uncoated straw combine blades.
2. To study economic feasibility of cryogenic coated blades.

The wear analysis of the high carbon steel specimen was done in Tribology laboratory of NIT, KUK, Kurukshetra, whereas, field testing was done at farmers field in Ludas and Sahpur village of Hisar district. In laboratory experiment three replication of load

(15, 20 and 25 N), time (150, 300 and 450 s) and sliding velocity (1.31, 2.61and 3.92 m s^{-1}) were used for wear analysis. The wear analysis was done by using Pin on disc wear testing machine. The diameter and the length of the coated and uncoated high carbon steels specimens for testing were 10 and 35mm, respectively. In field testing, cryogenic coated and uncoated cutter bar blades (A type) and chopping blades (M type) were fixed in straw combine and evaluated on weight and dimension basis. Based on the laboratory and field results, the following conclusions were drawn:

- The wear loss for the uncoated specimen was significantly affected by load (70%) followed by sliding velocity (20%) and time (10%). However, in the case of the coated specimen, the wear was significantly dominated by applied load only.
- The time and sliding velocity has negligible effect on the coated specimens.
- The FE-SEM analysis showed that the uncoated specimen has deep grooves on the wear surface, whereas the wear from the coated surface has uniformity all over the surface. This indicated that the cryogenic treatment improved the grain structure and intermolecular bonding of the specimen.
- The Energy Dispersive Spectroscopy (EDS) helped in identifying the constituting elements and their percentage change in respective uncoated and coated specimens. Due to this changing percentage of elements in the specimens, the cryogenically coated surface showed greater hardness than uncoated specimens.
- The cost of cryogenic coating of cutter bar blade (A type) and chopping cylinder blade (M type) was Rs 2.25 and Rs. 2.50 respectively.
- The percentage increase in the cost of the cutter bar and chopping cylinder blades due to cryogenic treatment increased by 9.38% and 13.6 % respectively.
- The cryogenic treatment resulted in 75.0 % increase in wear resistance of coated cutter bar blade (A type) as compared to uncoated blades.
- The cryogenic treatment resulted in 71.15 % increase in wear resistance of coated chopping cylinder blade (M type) as compared to uncoated blades.
- The life of cutter bar blade (A type) and chopping cylinder blade (M type) increased by 75% and 70%, respectively.

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APPENDIX: A-I

Wear (%) of uncoated cutter bar and chopping cylinder blades (A & M type) on weight basis

Sr. No.	Weight before test (g)		Weight after test (g)		Wear (%)	
	Cutter bar blade	Chopping cylinder blade	Cutter bar blade	Chopping cylinder blade	Cutter bar blade	Chopping cylinder blade
1	64.85	70.90	62.30	70.34	3.93	0.79
2	64.30	70.30	62.70	69.63	2.48	0.95
3	65.90	69.90	63.70	68.52	3.33	1.97
4	64.40	70.00	63.10	68.68	2.01	1.89
5	63.10	70.40	61.60	69.12	2.37	1.81

APPENDIX: A-II

Wear (%) of coated cutter bar and chopping cylinder blades (A & M type) on weight basis

Sr. No.	Weight before test (g)		Mass after test (g)		Wear (%)	
	Cutter bar blade	Chopping cylinder blade	Cutter bar blade	Chopping cylinder blade	Cutter bar blade	Chopping cylinder blade
1	64.70	70.40	64.43	70.17	0.41	0.32
2	64.00	69.90	63.59	69.47	0.64	0.61
3	64.11	70.80	63.50	70.54	0.95	0.36
4	63.70	70.10	63.10	69.79	0.94	0.44
5	64.80	69.40	64.45	69.16	0.54	0.35

APPENDIX: B - I

Wear (%) of uncoated cutter bar blades (A type) on dimension basis

Blade Assembly	Sr. No.	Dimensions before test (mm)			Dimensions after test (mm)			% Wear		
		Length	Width at tip	Width at 30 mm from tip	Length	Width at tip	Width at 30 mm from tip	length	At tip	At 30 mm from tip
Cutter bar	1	84.59	14.60	50.12	84.33	13.02	46.55	0.31	10.82	7.12
	2	83.51	14.70	50.73	83.01	12.13	48.78	0.60	17.48	3.84
	3	83.87	14.72	50.43	83.47	12.80	47.63	0.48	13.04	7.38
	4	83.95	13.96	49.78	83.61	11.74	46.12	0.40	15.90	7.35
	5	83.59	14.03	50.35	83.22	11.96	47.37	0.44	14.75	5.91

APPENDIX B-II

Wear (%) of coated cutter bar blades (A type) on dimension basis

Blade Assembly	Sr. No.	Dimensions before test (mm)			Dimensions after test (mm)			% Wear		
		Length	Width at tip	Width at 30 mm from tip	Length	Width at tip	Width at 30 mm from tip	length	At tip	At 30 mm from tip
Cutter bar	1	84.18	14.58	50.80	83.80	13.34	48.69	0.38	8.50	4.15
	2	84.25	14.18	50.80	83.94	12.70	48.98	0.31	10.43	3.58
	3	84.13	14.77	50.68	83.83	13.17	47.45	0.35	10.83	6.37
	4	84.30	14.68	51.48	83.92	13.26	48.88	0.38	9.67	5.05
	5	83.97	14.70	51.44	83.66	13.13	49.76	0.37	10.68	3.26

APPENDIX: B-III

Wear (%) of uncoated chopping cylinder blades (M type) on dimension basis

Blade Assembly	Sr. No.	Dimensions before test (mm)			Dimensions after test (mm)			% Wear		
		Length	Width at tip	Width at 30 mm from tip	Length	Width at tip	Width at 30 mm from tip	length	At tip	At 30 mm from tip
Chopping cylinder	1	80.91	37.46	60.80	80.20	35.76	59.08	0.87	2.94	2.83
	2	80.91	38.90	60.30	80.18	37.28	58.12	0.90	4.16	3.61
	3	81.72	38.05	60.00	80.90	36.63	58.06	1.00	3.73	3.23
	4	80.75	37.64	60.12	79.96	36.18	58.27	0.97	3.88	3.07
	5	80.68	37.13	60.60	80.03	36.60	58.83	0.80	1.42	2.92

APPENDIX: B-IV

Wear (%) of coated chopping cylinder blades (M type) on dimension basis

Blade Assembly	Sr. No.	Dimensions before test (mm)			Dimensions after test (mm)			Wear (%)		
		Length	Width at tip	Width at 30 mm from tip	Length	Width at tip	Width at 30 mm from tip	length	At tip	At 30 mm from tip
Chopping cylinder	1	81.10	37.13	60.89	80.20	35.68	58.76	1.10	3.90	3.49
	2	81.42	38.96	61.20	80.28	37.24	58.10	1.40	4.41	5.06
	3	81.77	38.28	60.31	80.92	35.48	57.68	1.03	7.31	4.36
	4	80.99	38.82	60.19	80.18	36.58	57.22	1.00	5.77	4.93
	5	80.80	38.27	60.49	80.01	36.55	58.40	0.98	4.49	3..45

APPENDIX: C- I

Wear loss measurement in laboratory experiments on Pin on disc wear tester machine

Sr. No.	Load (N)	Sliding velocity (m s^{-1})	Time (s)	Sliding distance (m)	Wear loss (g)		Specific wear rate × 10^{-7} (mm^3 Nm^{-1})	
					Uncoated	Coated	Uncoated	Coated
1	15	1.31	150	196.50	0.0010	0.00080	0.4321	0.3457
2	15	2.61	300	783.00	0.0020	0.00110	0.2169	0.1193
3	15	3.92	450	1764.00	0.0024	0.00131	0.1554	0.0630
4	20	1.31	300	393.00	0.0025	0.00138	0.4051	0.2236
5	20	2.61	450	1174.00	0.0027	0.00153	0.1465	0.0830
6	20	3.92	150	588.00	0.0028	0.00165	0.3033	0.1787
7	25	1.31	450	273.79	0.0033	0.00177	0.6141	0.3294
8	25	2.61	150	1085.76	0.0035	0.00182	0.1642	0.0845
9	25	3.92	300	2446.08	0.0050	0.00199	0.1041	0.0414

ABSTRACT

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(An abstract of the thesis submitted to CCS Haryana Agricultural University, Hisar, in partial fulfillment of the requirements for the degree of Master of Technology in Farm Machinery and Power Engineering)

The harvesting machines (combine, reaper and straw combine) are developed to overcome the shortage of labor and timely operations and also to facilitate the multi cropping sequence in India. The cutting blades are made up of high carbon steel having carbon content ranging from 0.60 to 1.00 percent. The carbon is the main element for higher strength and hardness of cutting steel blades. However, during cutting at high temperature and in abrasive environment, these cutting materials faces excessive surface degradation which ultimately reduces the life of the blade and increased cutting cost of the machine. In recent times the cryogenic treatments have positive effect to improve the wear resistance, hardness and life of the cutting tools. The present study was undertaken to improve the mechanical properties of cutter bar blade (A type) and chopping cylinder blade (M type) of straw combine with cryogenic treatment. For this, the laboratory testing was done in Tribology laboratory of NIT, KUK, Kurukshetra, whereas, field testing was done at farmers field in Ludas and Sahpur village of Hisar district. In laboratory experiment three replication of load (15, 20 and 25 N), time (150, 300 and 450 s) and sliding velocity (1.31, 2.61and 3.92 m s^{-1}) were used for wear analysis. The wear analysis was done by using Pin on disc wear testing machine. The diameter and the length of the coated and uncoated high carbon steels specimens for testing were 10 and 35mm, respectively. In uncoated specimens, the wear was significantly affected by load followed by sliding velocity and time, whereas in coated specimen, the load was the only significant parameter to affect the wear properties of the specimens. The time and sliding velocity had negligible effect on the coated specimens. During field testing, the coated and uncoated blades were installed on the straw combine and operated for 38.33 hours. The wear of the blades was analyzed with respect to the weight and dimensions of the blades before and after work. The wear (%) in cutter bar and chopping cylinder blades for uncoated and coated were found as 2.82, 0.69 and 1.48, 0.41%, respectively. The cryogenic treatment resulted in increase of 9.38 and 13.61% cost of the cutter bar and chopping cylinder blades, respectively. This increased cost was fully justified by the increased cutter bar and chopping cylinder blade life by 75 and 72 %, respectively.

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