"Surface Engineering of Tool Steel & Duplex Stainless Steel"

M. Tech. Thesis

By

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M. Tech. (2018-2020)



DEPARTMENT OF METALLURGY ENGINEERING AND MATERIALS SCIENCE

INDIAN INSTITUTE OF TECHNOLOGY INDORE

June 2020

"Surface Engineering of Tool Steel & Duplex Stainless Steel"

A THESIS

Submitted in partial fulfillment of the Requirements for the award of the degree

of

Master of Technology

By

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DEPARTMENT OF METALLURGY ENGINEERING AND MATERIALS SCIENCE

INDIAN INSTITUTE OF TECHNOLOGY INDORE

June-2020



INDIAN INSTITUTE OF TECHNOLOGY INDORE CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "Surface Engineering of Tool Steel & Duplex Stainless Steel" in the partial fulfillment of the requirements for the award of the degree of MASTERS OF TECHNOLOGY in METALLURGY ENGINEERING and submitted in the DEPARTMENT OF METALLURGY ENGINEERING AND MATERIALS SCIENCE, Indian Institute of Technology Indore, is an authentic record of my work carried out from July 2018 to June 2020 under the supervision of Dr. Santosh S. Hosmani, Associate Professor, IIT Indore.

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Acknowledgments

I express my deep sense of gratitude to the Almighty for guiding me and giving patience throughout this duration. Inspiration and guidance are valuable in all aspects of life. This venture has received the enthusiastic support of my Guide, **Dr. Sanotsh S. Hosmani**. Constant encouragement, motivation, and enthusiasm from my guide helped me to move forward with an investigation in depth. I take this opportunity to express my gratitude to **Prof. Neelesh Kumar Jain, Director, IIT Indore,** for providing the essential facilities, valuable guidance, and cooperation.

I am pleased to express my gratitude towards my PSPC members **Dr. Parasharam M. Shirage** and **Dr. Sunil Kumar**, for their guidance and support. I am thankful to **Dr. Vinod Kumar**, **HOD**, **Dept. of MEMS** for his support and cooperation. I am thankful to all **faculty members** of the **Department of Metallurgy Engineering and Materials Science** for their guidance and support.

I acknowledge and thankful to the SIC facility in IIT Indore, Metal Forming & Surface Engineering lab, for allowing me to conduct my experiments and study. I am thankful to MHRD, Govt of India, for providing fellowship during my Master studies.

Last but not least, I cannot forget the support and encouragement received from my family, and my colleague Mr. Aditya Litoria, Mr. Digvijay Singh, Mr. Manoj D. Joshi and Mr. Vikesh Kumar (research scholars, IIT Indore) and Mr. Mayur Dhake without which this journey would not have been possible.



Darshan Dange

Abstract

The approach of the present work is directed towards the tribological study of two different steel materials viz. AISI H13 tool steel majorly used in hot forging and forming industries and AISI 2205, duplex stainless steel used in petrochemical, marine, nuclear, chemical, automotive, and paper industries. AISI 2205 duplex SS steel contains nearly same amounts of austenite ' γ ' and ferrite ' α ' and thus, dualphase microstructure leads to an excellent combination of mechanical properties and better corrosion resistance lagging with its reliable performance against frictional forces. Surface modification of steel surfaces introduces better response against wear degradation phenomenon. Improved surface characteristic of the material was achieved by deploying different surface treatments like surface mechanical attrition treatment (SMAT), plasma-nitriding and a subsequently a duplex treatment (SMAT + plasma-nitriding).

In current work, ion plasma nitriding was performed at 460°C for 5 hrs and 525°C for 10 hrs in case of H13 tool steel and DSS 2205 steel specimen, respectively. Different specimens were characterized using optical microscopy, FE-SEM, XRD, hardness. Plasma-nitriding introduces hard nitride layer of average thickness \approx 14 µm and \approx 9 µm in H13 tool steel and DSS 2205 steel specimen respectively. Surface hardness, approximately two and three times in HRC scale was achieved as a result of plasma-nitriding for H13 and DSS 2205 respectively. Fe₃N, CrN and Cr₂N are nitride phase was formed after the nitriding treatment in case of H13 whereas expanded austenite also present in DSS 2205 steel material.

Dry-sliding wear test was performed on both bare as well as nitrided specimen using various applied load and sliding velocity. Steel surfaces with hard nitride layer shows better wear performance compared to untreated one. Plasma nitrided AISI H13 shows maximum 98% of improvement in wear resistance than as-received at 0.5 m/s sliding velocity and 15 N applied load. However, duplex treated AISI 2205 steel shows 97% enhancement in wear resistance at 1 m/s sliding velocity and 10 N applied load. Therefore, Plasma nitride AISI H13 and duplex treated AISI 2205 steels can be used in tribological applications in dry sliding conditions.

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Nomenclature

List of Abbreviation and Symbols

SMAT	Surface Mechanical Attrition Treatment
SPD	Severe Plastic Deformation
SFE	Stacking Fault Energy
CRS	Compressive Residual Stress
COF	Coefficient of Friction

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Chapter 1

Introduction

1.1 General Introduction

Steels are known for their high tensile strength with relatively low cost, and thus significantly used as a primary base component in several industrial applications including infrastructure, forming and tool industry, automobiles, etc [1]. However, their low surface hardness restricts its wider approach towards different corners of industrial applications [2]. Surface engineering has the potential to bring essential improvement to steel components thus increasing its workability for wider acceptance and further enhance material's life. Surface engineering incorporates vast varieties of surface improvement techniques among which improving surface hardness of the material has gain lot of interest in application aspects [3]. Plastic deformation (like shot pinning surface attrition and mechanical treatment) and thermochemical processes (like Nitriding, Carburizing, Carbonitriding etc.), surface coatings are some of the techniques deployed in industries to enhance surface hardness of steel [3], [4].

Steel based components used in different industrial applications has to undergo various surface degradation phenomenon. Wear, corrosion, oxidation is considered to be the major ones which leads to material failure. Engineering components are also subjected to extreme working conditions such as higher stress, fatigue, and abrasion, as well as direct corrosive attack by the environment [2], [5], [6]. Due to these extreme working conditions, degradation or material failure starts from the surface. Therefore, it is crucial to improve the surface characteristics of the material to improve the performance, efficiency, and material life. Thus, surface engineering becomes the most reliable route to overcome these associated challenges [2], [4], [7].

1.2 Introduction to Surface Engineering

Today, Surface engineering is applied as a processing technology to a wide range of industrial applications. It includes several techniques that are capable of producing engineered surfaces with improved characteristics. These modified surfaces show intensified performance having better wear, corrosion, and fatigue resistance. Surfaces having multicomponent properties as well as surfaces with multilayer architecture having upgraded performance can be produced by surface engineering techniques [2]–[5], [7]. Broader classification of surface engineering techniques and their principle approach includes (Figure 1) [3], [8]:

- a. Producing engineered/modified surfaces without affecting surface chemistry of the base material.
- b. Producing engineered/modified surfaces by introducing required and appropriate alteration to the surface chemistry of the base material.
- c. Producing engineered/modified surfaces using an additional coating layer having superior characteristics.

Surface engineering has emerged as a characteristic route that adds surplus characteristics to the manufactured (using different production techniques) metallic, polymeric or ceramic materials [3], [8], [9]. Successful application of surface engineering techniques to the wide range of materials may lead to the use of low-grade material (with poor characteristics) for wide range of applications after its surface treatment [2], [8].



Figure 1: Introduction to Surface Engineering [3].

1.2.1 Producing engineered/modified surfaces without affecting surface chemistry of the base material

In this process of surface treatment, the surfaces of different materials are modified without transforming its chemical properties and internal characteristics. The chemistry of the base material remains intact to the prior one. The properties like hardness changes due to microstructural modification which accounts for enhanced wear, and fatigue properties of the material. It includes both thermal and mechanical treatments. Some of the examples are:

1.2.1.1 Surface hardening

In this method, surface modification of steel surfaces can be achieved by localized heating and quenching, without any chemical change of the surface. Modification of steel surfaces using induction, flame, laser, and electron beam hardening are some of the characteristic techniques falls under this category [10].

1.2.1.2 Laser melting

Laser surface treatment is extensively used to modify near surface areas of machine element. This process is basically referred to as laser transformation hardening to distinguish it from laser surface melting phenomena. No compositional changes are produced by this process and considered to be a powerful technique to harden the surfaces of ferrous materials [11].

1.2.1.3 Shot Peening

Shot peening is a cold forming process that introduce CRS layer near to the surface region, improving the mechanical properties of the components. This ensures for better resistance to fatigue and stress corrosion [4], [12].

1.2.2 Producing engineered/modified surfaces by altering surface chemistry of the base material.

1.2.2.1 Thermo-chemical Diffusion

In thermo-chemical diffusion method, the compound of the material surface is modified under temperature based controlled reaction with elements such as carbon, nitrogen, and boron. The diffusion method can be easily applied to the entire surface of the material or to a specific portion. This method is used when plenty components are to be produced [8], [10].

1.2.2.2 Ion Implantation

Ion implantation is a surface modification process works on the principle of surface modification using high energy ions. High energy ions of any hardening specie at high energy are incorporated into a base material. Ion implantation technique using ions of nitrogen is extensively used to enhance corrosion and tribological properties of steel [11], [13].

1.2.3 Producing engineered/modified

surfaces using surface coating technique

Surface coating technique has emerged as one of the most widely accepted technique of surface engineering in the present scenario. Compared to other techniques falls under surface engineering, this method is most reliable for large production rates. Disadvantages related to this technique includes high cost related to material as well as process (like PVD, PACVD, CAPVD, Sputtering etc.) [9], [11], [13].

1.3 Introduction to Tribology

Tribology is term taken from Greek letter 'tribos' means rubbing. Tribology defined as "It is the science which deals with interacting bodies which are in relative motion" [14], [15]. Tribology field contains the analysis and investigation of all types of machine components which encompass wear, friction, and lubrication (Figure 2).



Figure 2: Tribology Triangle [14]

Machine components under relative motion may lead to rise of frictional forces at the contacting surfaces. These frictional forces can have serious impact on the machine components varying from mild to severe [15]. Thus, proper identification of its degree of effect and methods of its controlling should be derived to increase life of machine components and its efficiency. Existing wear at the contacting surface can cause severe damages which could even lead to failure of the machine components. Thus, proper selection of material and lubricants becomes very important to counter the effects of frictional forces [14].

1.4 SMAT

The surface mechanical attrition treatment (SMAT) is in which the metal surface subjected to severe surface deformation by the collision of hardened flying steel balls energized by vibrating plate, which causes the strain hardening and grain refinement near the surface area [7], [16]. SMAT process increases the defects, and number of grain boundaries, or both by the gathering of higher applied strain. This gathered strain is achieved through the repetitive and random impact of hardened steel balls on the specimen surface; consequently, the grain refinement of the old coarse grains happens without alteration of chemistry [4], [16].

1.5 Ion-Plasma Nitriding

Ion-Plasma nitriding involves diffusion of high energy ions of nitrogen gas into the surface of ferrous material to produce hard nitride surface layer. Plasma nitriding is generally performed at the temperature range between 450 to 590°C (depends on the category of the steel), which is below the austenite formation temperature for ferrite steels [8], [11].

Plasma-nitriding as a surface hardening technique uses glow-discharge approach to introduce nascent (elemental) nitrogen to the material followed by its subsequent diffusion into the material surface. The plasma of nitrogen ions is formed in a high vacuum chamber using high, and these high energy ions were made to accelerate towards the workpiece. On account of continuous ion bombardment, the material surface gets reacted with nitrogen ions thus producing hard nitride layer with uniform depth, chemistry and least distortion to the material [10], [11].

Chapter 2

Literature Review

Present literature review primarily focuses on identifying widely accepted surface engineering techniques and their effect on changing performance of steel components. Significant focus lies in dealing with mechanical and thermochemical methods of surface treatments.

Present approach towards use of steel components lies with introducing priory a surface layer with enhanced characteristic to ensure for its better performance and increased service life. These surface layers can be produced by different characteristic approaches including [10]:

- Mechanical
- Thermal
- Thermo-mechanical
- Thermo-chemical
- Physical
- Chemical
- Electrochemical

Surface modification techniques works on a top-down approach, where the material surfaces are restructured with or without changing chemical composition of the base material. Shot peening, sandblasting, surface mechanical attrition treatment (SMAT), flame and induction hardening are some of the surface modification techniques that do not introduce any change to the chemical composition of the base material, whereas carburizing, nitriding, carbo-nitriding and boronizing are some of widely accepted surface modification techniques that results into restructured surfaces with desirable alteration in composition of material surface [17].
Contrary, coating techniques adopts bottom-up approach, where the surface layer of desired composition is deposited on the material surface. Chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma processing, electrodeposition, and sputtering are some of industrial approaches used for surface coating [4].

2.1 SMAT

Mechanical routes of surface modification are based on utilizing the pressure or kinetic energy of the tool or counter body (in the form of steel balls, sand particles etc.) to achieve the desired effect on the substrate material. Surface mechanical attrition treatment (SMAT) is one of the characteristic routes based on mechanical surface modification principle [3], [16], [18].

2.1.1 Introduction

SMAT utilizes the effect introduced by repetitive impacts or peening of shots (majorly high strength steel balls) to improve the material surface characteristics. The influence of SMAT is noticed on various metals [19], and alloys [20], [21]. Grain refinement that resulted using SMAT process can range up to micro to the nano-level [4], [21]. Figure 3 shows the schematic of SMAT setup.



2.1.2 Operating Principle of SMAT

Surface mechanical attrition treatment introduces strainhardening at the material surface to produce hard surface layer. On account of repetitive impact produced on specimen surface by the randomly moving balls/shots inside the SMAT cabin, an accumulative strain is obtained [22].

This accumulation of the applied strain introduces the defects as well as surplus grain boundaries near to the surface region. Thus, grain refinement of the prior coarse grains without alteration of composition is achieved. The mechanism of refinement of grains mainly depends on the crystallographic structure and stacking fault energy (SFE) [4], [23].

- In the high SFE materials, the mechanism of refinement of grains is typically through the accumulation and destruction of dense dislocation walls and dislocation tangles [16], [22].
- In the case of low SFE materials, the mechanism of refinement of grains is dominant by twinning [16], [22].

2.1.3 SMATed surface analysis

The impact of flying balls during SMAT introduces the maximum strain and strain rate at the outermost surface, and a gradient exists in the quantity of strain and strain rate along with the depth from the SMATed surface to the base matrix. The sequence of the layers across the cross-section of the SMATed surface are as follows (Figure 4) [19], [22]:

- Nano-grains at the top layer,
- Refined structure,
- Deformed grains,
- Strain free coarse grain matrix.



Figure 4: Schematic of the microstructural and strain and strain rate distributions inside the SMATed surface [18]

2.1.4 Effect of SMAT on Hardness

The increase in hardening in the near-surface region than the after SMAT is attributed due to planer dislocation movement causing the accumulation of the mechanical twins are present near the surface region of the steel [4], [16]. This accumulation of mechanical twins and increase in hardness is depends on the various SMAT parameters (Table 1).

S.N.	Material	SMAT Parameter		Hardness		Deference
		Ball Size (mm)	Time (min)	Non- treated	SMATed	
1.	DSS 2205	6	60	250 HV	350 HV	[21]
2.	SS 304L	3	60	190 HV	420 HV	[16]
3.	SS 316	6	60	1.9 GPa	3.8 GPa	[22]
4.	SS 316	-	30	2 GPa	4 GPa	[4]
5.	SS 304	8	60	190 HV	380 HV	[16]

Table 1: Comparison of SMAT parameter and Hardness.

2.1.5 Effect of SMAT on Nitriding

SMAT process coupled with surface plasma nitriding worked as a duplex surface treatment in order to obtain the higher thickness of diffused hard nitride layer [7]. The increase in the diffusion of nitrogen after SMAT is observed due to the higher availability of dislocation density and grain boundary near the surface region, which provides the extra pathway to nitrogen for diffusion (Figure 5) [24]–[26].



Figure 5: Schematic for the mechanism of nitrided layer formation in Non-SMATed and SMATed Specimen [24].

2.1.6 Effect of SMAT on Wear

The wear resistance of several materials after SMAT process has been investigated. Lei Wen et al. [27] demonstrated that iron-rich layer reduces the corrosion resistance whereas, wear resistance was improved due to combine effect of improved surface hardness, grain refinement and lubricious nature of layer of 2024 Al alloy. In order to optimise the SMAT parameter for improved wear resistance behaviour Manoj D. Joshi et al. [21] reported that the 50% coverage area with 6mm ball diameter and 60 min SMAT duration gives maximum output response for AISI 2205 DSS.

2.1.7 General Advantages and disadvantages of SMAT

- A significant increase in strength without any noticeable reduction in ductility can be achieved [23].
- Different alloy system shows a combination of high ductility with improved tensile strength and yield strength after SMAT under variable operating conditions [4][23][16].
- SMAT improves the material hardness with grain size refinement [4][16]. It also increases dislocation density and results into the formation of martensite in the nanocrystalline surface layer.
- The thickness of the diffused layer produced by any thermo-chemical treatment is found to be higher in case of SMATed specimens compared to non-SMATed specimen because SMAT develops the functional structure of the surface due to high atomic diffusive reactivity [4][16].
- A noticeable improvement in the mechanical properties after SMAT process is evident and hence material surfaces with improved fatigue strength, corrosion and wear resistance can be achieved [4][16],
- The fatigue life of the material is found to vary directly in relation with size of the ball/shots used in SMAT process as well as on strain rate. Fatigue life of the material improves further with increasing ball size and strain rate. The nanocrystalline surface layer and nano-

grains induced by SMAT can improve the overall fatigue life [4].

- The combined effect of the nanocrystalline surface layer, residual compressive stress, and work-hardened surface region enhances the fatigue life of the material [4].
- The dominant microstructural mechanism of dislocation activities in surface nano-crystallization induce by the SMAT process are influenced by the presence of ample amount of carbide, and mechanical twinning at starting stage and followed by dynamic recrystallization, phase transformation, and the transition from twinning to dislocation slip with increasing strain [4].
- Defect (like porosity) free and contamination-free surfaces with grain size refinement ranging from nanometres to micro-meters is observed [22], [12].

Disadvantages

- Flat surface is required for the SMAT process and the sample size is constrained and depends on SMAT cabin size.
- In SMAT process spherical ball with smooth surface is essential otherwise ball will erode and damage the specimen surface.
- SMAT process modifies only surface layer of the specimen while SPD technique like high pressure torsion and accumulative roll bonding modifies the whole work piece [18].

2.2 Nitriding

2.2.1 Introduction

Nitriding is a world-wide accepted surface hardening technique for different categories of steel components (cold and hot worked steel, hardened and tempered steel, high alloyed steels etc.) [28]. Nitriding is a temperature assisted surface treatment occurs at the surface of ferrous material through the mechanism of thermal diffusion or plasma assisted thermal diffusion. These mechanisms introduce nitrogen to the material surface forming hard surface nitride layer. Temperature assisted nitriding process results into formation of a nitriding zone basically divided into two sub regions as: a top layer of limited thickness (thickness ranging from 2-5 μm) rich in metal based hard nitride phases (Al-N, Cr-N, etc) and a diffusion zone of greater thickness (thickness ranging from 10-100 µm) formed by the nitride of iron and alloying elements present in the host material [29], [30]. Region of hard nitride phases provide surplus strength in terms of higher hardness and toughness making host material more wear and tear resistant. Diffusion zone on the other hand is formed by the occupancy of interstitial sites of the host material by the nitrogen atoms [28], [31]. This retention from the nitrogen atoms induces lattice expansion causing generation of compressive stresses, thus introducing greater toughness and wear resistant characteristics[28], [29], [31].

Proper handling to the process parameters of Nitriding process (process parameters as: process time, furnace temperature, gas flow rate, etc.) results into the formation of uniform and defect free nitride region of greater thickness. This also helps to achieve least distortion. Results of nitriding process also include formation of hard nitride top layer (ϵ -Fe_{2,3}N and γ -Fe₄N) popularly known as 'white layer' (Figure 8). This layer possesses brittleness and required to be eliminated since it can result into crack propagation into the material surface under variable loading conditions [30], [32], [33]. Surface nitriding of Duplex stainless steel materials (having equal proportion of ferrite and austenite phases) results into the formation of solid solution of (Fe, Cr)₂N possess greater hardness and thus inducing superior wear resistant characteristic to the material[28], [31], [34].

2.2.2 Types of Nitriding Processes

The process of nitriding can be successfully carried out by introducing proper source of nitrogen into the host material. Different conventional techniques used for nitriding treatment include gas nitriding, liquid (salt-bath) nitriding, ion implantation and plasma ion nitriding and advanced process of nitriding include laser nitriding [11], [28], [31]. The conventional techniques of nitriding are discussed below in detail.

2.2.2.1 Gas Nitriding

Gas nitriding process involves feeding ammonia into the closed nitriding chamber. Ammonia being a nitrogen source is used in the nitriding process and the components to be nitride placed inside the chamber maintaining temperature ≈ 510 °C inside the chamber [35], [36]. Results of nitriding includes formation of a top compound layer and a diffusion zone normally termed as "case". The hardness is found to be decreasing along the case depth. Dissociation of ammonia takes place as per the following chemical reaction:

$$2\mathrm{NH}_3 \rightarrow \mathrm{N}_2 + 3\mathrm{H}_2$$

Atomic nitrogen as a result of dissociation forms and find ease to get absorbed by the steel surfaces. The driving force for the nitriding is the nitrogen potential in the gaseous atmosphere [37]. The process is considered to be very effective for nitriding of complicated shapes and structures.



Figure 6: Schematic of Gas Nitriding [29]

2.2.2.2 Salt Bath Nitriding

Salt bath nitriding process use different sources of cyanides and cyanates for nitriding treatment. The parts to be nitrided immersed into a salt bath containing molten salt mixture. The salt mixture had a proportion of ≈ 60 to 70% by weight NaCN and ≈ 30 to 40% KCN [38].

In order to avoid any discrepancy in hardness value across the nitrided surface, it is advisable to keep uniform concentration of nitrogen source for the entire surface region [37]. Nominal temperature range adopted for this treatment is 550-570°C. During the reaction taking place, salt bath dissociates to gives off carbon and nitrogen according to the following expression [8]:

$$4NaCNO \rightarrow 2NaCN + Na_2CO_3 + CO + 2N$$

 $3Fe + 2CO \rightarrow Fe_3C + CO_2$

Quenching of treated parts in warm water after the completion of process can produce supersaturated solid solution of nitrogen in α -iron, thus enhanced fatigue life of the material resulted [11].



Figure 7: Schematic of Salt Bath Nitriding [11]

2.2.2.3 Ion Implantation

Surface nitriding of ferrous material using ion implantation is one of the cleanest and contamination free process. In this process high energetic ion beam of nitrogen atoms (beam energy ranges between 40keV-1Mev) penetrates the surface of the host material and modifies chemical composition of near surface region. The process of nitriding of ferrous materials using ion implantation technique could be successfully carried out at low temperatures. A thick micron nitride layer could be easily produced by ion implantation [11].

2.2.2.4 Plasma Nitriding

Plasma or Ion nitriding technique has evolved as a development to other conventional techniques of nitriding. Plasma nitriding is case hardening thermo-chemical process uses glow discharge approach for introducing elemental nitrogen to the material surface followed by its subsequent diffusion into it [11], [28], [31]. In a vacuum, nitrogen ions in the form of plasma are accelerated to impinge on the substrate surface [8]. Operating temperature in plasma nitriding lies in the range of 400-590°C, produce nitrided surfaces with dimensional accuracy. Plasma nitriding also facilitates the control over case depth and chemical composition.

The working principle of plasma nitriding is described as: If two different electrodes having different potential are positioned in a surrounding gas atmosphere under reduced pressure (of the order of 10⁻⁴ to 10⁻³ mbar), and if increasing negative bias voltage is applied, then as a result a glow (at a minimum specific value of voltage) is formed around the electrode of lower potential. The substrate material to be nitrided placed inside the chamber completely covered by the glow. As the treatment progresses, interaction between the ionized nitrogen atoms in the plasma and surface starts, resulting into the start of diffusion of nitrogen atoms into the surface of host material forming nitrogen rich nitride layer [11].



Figure 8: Schematic of Compound layer and Diffusion Zone structure of nitrided Steel [8].



Figure 9: Schematic of Plasma Nitriding

As discussed earlier, a two layered architecture (hard compound/white layer on the top and a softer diffused layer beneath it) of nitrided region is formed. This two-layered architecture basically defines the properties possessed by the host material. As elucidated in various other studies that the superior corrosion and wear resistance are the characteristic of compound layer and fatigue strength is the characteristic of diffused layer. Availability of nitrogen contents during the reaction process basically governs the formation of nitride phases during nitriding. Clear indication of limited solubility of 0.12 wt% nitrogen in ferrite phase at 590°C is seen from Fe-N phase diagram in Figure 11.



Figure 8: Phase diagram of Fe-N System [11]

Industrially applicable technique of plasma nitriding makes use of a mixture of H₂ and N₂ during plasma nitriding of ferrous materials. Increased thickness of nitride layer is the resultant advantage of using hydrogen along with nitrogen in plasma nitriding [39]. H₂ and N₂ in different proportion are used depending on the desirable thickness of nitride layer. Optimum amount of hydrogen (< 50%) is prescribed to be used during nitriding process since using hydrogen above this may retard the growth of nitride layer [11], [40]. Optimum ratio 1:4 for H₂/N₂ is advisable for the nitriding treatment. Plasma nitriding depends on various process parameters such as process time, temperature, bias voltage, gas mixture as well as on the presence of alloying elements. Nitrogen has a great tendency of forming nitride phase with elements like Al, V, Ti, Cr etc. which is directly correlated to the strength of the formed phases. Increase in the percentage of alloying elements in the base material, lower will be the resultant nitride layer thickness [11], [34].

2.2.3 General Advantages and disadvantages of Nitriding

- Nitriding has low process temperature over the other case hardening process [36].
- Plasma nitriding has high dimensional stability compared to other heat treatment processes [41], [42] and provides batter control of case chemistry.
- Nitrided surpasses high fatigue strength and low fatigue notch sensitivity [43], and high resistance to tempering and high-temperature hardness [34].

Chapter 3

Scope of the Study

Now a days one of the major issues is developing innovative and economical surface modification processes using easily available and low-cost material that can impart batter qualities to the surface of the material without altering bulk properties of the material.

In this process, for the surface modification microstructural studies can be carried out and modification in surface layer morphology and surface hardness can be studied for two different grades of steel.

During literature review, it was found that no sufficient work has been done to know about the tribological behaviour of the tool steel and duplex stainless steel.

3.1 Gap Analysis

- Limited study is performed to check the enhanced surface characteristic of H13 tool steel after Nitriding treatment and its tribological study.
- Tribological response of Duplex 2205 stainless steel after SMAT, Nitriding and duplex treated (SMAT+ Nitriding) was least explored.

3.2 Objective

- Study the tribological behaviour of nitrided AISI H13 Tool Steel.
- Study the effect of SMAT, Nitriding, and Duplex (SMAT + Nitriding) treatment on the tribological behaviour of 2205 duplex stainless steel.

3.3 Timeline of the Study

Project Duration: 12 Months (July 2019-June 2020)



Chapter 4

Experimentation Experimentation of AISI H13 Tool Steel and AISI 2205 DSS

4.1 Substrate preparation

For the present study, square samples of H13 tool steel with dimension $45 \times 45 \times 4$ mm and cylindrical samples of SS 2205 with dimension ϕ 60×4 mm were cut and prepared by wire electric discharge machining (EDM) for plasma nitriding and wear test experiments. The flat surfaces of the specimen were ground and polished at a final step of 1µm alumina suspension to achieve a mirror-like surface finish for plasma nitriding. The specimen was cleaned with an ultrasonic bath cleaner for 30 minutes at 45°C temperature under de-ionized water. After that, the samples were cleaned with acetone solution.

4.2 SMAT

In-house developed surface mechanical attrition treatment (SMAT) setup was used for the surface treatment of AISI 2205 Duplex Stainless Steel. This setup was based on the concept of electromagnetic vibrations. The electromagnet was magnetized and demagnetized by supplying the alternating current (AC). The magnitude of the current follows the sinusoidal waveform with respect to time, and consequently, the magnetic force generates in the electromagnet, which follows the same waveform pattern. When the electromagnet gets magnetized, it attracts the mild steel plate, which is attached below the SMAT cabin. The optimized SMAT parameters were used for further experiments. In SMAT setup, hardened AISI 52100 steel balls of size 6 mm are used to randomly hit the specimen to deform its surface and oilhardened non-shrinkable steel (OHNS) plate used as a base. The ball speed was measured by using the high-speed camera and reported as the peening intensity. The 25% of cabin coverage by balls was identified as the most effective SMAT process parameter with a 45 mm gap between the vibrating oilhardened non-shrinkable steel plate and specimen surface (Table 2).

SMAT Parameters				
balls size	6 mm			
peening intensity	3 m/s			
cabin coverage by balls	25%			
Gap	45 mm			

Table 2: SMAT Parameters.

4.3 Plasma Nitriding

Polished surfaces of steel samples are subjected to plasma nitriding. The parameters of plasma nitriding for both H13 tool steel and SS 2205 are mentioned in table 3.

Plasma Nitriding Parameters						
	AISI H13 tool steel	AISI 2205 DSS				
Temperature	460°C	525°C				
Time	5 h	10 h				
Gas ratio (N2:H2)	30:30 litre/hr	60:150 litre/hr				

Table 3: Plasma Nitriding Parameters.

Plasma nitrided specimens were characterized using optical microscopy, X-ray diffraction analysis, Rockwell microhardness measurements, and sliding wear test.

4.4 Wear Test

Samples for wear experiments are polished up to 1000-grade polishing paper followed by slight diamond polishing. The samples were cleaned with acetone solution before wear test.

Sliding wear test is performed using the pin-on-disc tribometer of DuCom make (model: CM-9112). The ball of α -Al₂O₃ having a diameter of 8mm with the hardness of 120HRC is used as a counter body. The ball is loaded using a deadweight lever arm. The disc and ball were maintained at room temperature. The experiment is performed in accordance with ASTM G99. Experimental parameters used for sliding wear test are mentioned in table 4. As the experiment proceeds, the reduction in the height of the material per second due to wear loss is recorded by a linear variable differential transformer (LVDT) attached at one end of the lever arm. The frictional force exerted on the ball or pin by the disc is recorded using a piezoelectric sensor.

Wear Test Parameters							
Parameters	Details						
Material	AISI H13 tool steel	AISI 2205 SS					
Specimen condition	Nitrided and untreated specimen						
Standard	ASTM G99						
Dimension	45×45×4 mm	φ 45×4 mm					
Sliding Distance	1000 m	5000 m					
Sliding Speed	0.3 m/s & 0.5 m/s	0.5 m/s & 1 m/s					
Load	15 N, 25 N & 35 N	10 N, 20 N					

Table 4: Wear Test Parameters.

4.5 Characterization

4.5.1 Microstructure Study

Cuboid samples of 4 mm in edge length are used for microstructural analysis. Samples are hot mounted using the mounting press. The mounted samples are then polished using emery papers with the standard grit size up to 2500. Final polishing is done with 3 μ m diamond paste over the velvet cloth until the mirror finish is obtained.

After metallographic preparation, the microstructural examination was conducted by etching the surface of the sample with a suitable etchant. Etching preferentially oxidizes all the boundaries like grain, colony, and lath boundaries; thus, other matrix gets highlighted, which can be observed under an optical or scanning electron microscope. The etchant used for AISI H13 steel is Nital reagent having a composition of 5% nitric acid (HNO₃) and 95% ethyl alcohol (C_2H_5OH) by volume for microstructure analysis, whereas, Kalling's solution is used for AISI 2205 duplex stainless steel.

The etched samples were observed under an inverted optical microscope for microstructural study. Magnification from 20X to 100X was utilized to study the nitrided specimens. The coating thickness of nitrided specimens was measured using a digital camera attached to the optical microscope and by using analysis software. Readings for a coating thickness of specimens were taken at different locations. 8 to 10 readings were taken at different locations, and their arithmetic average was reported.

4.5.2 X-ray Diffraction (XRD) Study

X-ray diffraction technique was used to identify phases present in the coating as well as substrate steel. XRD patterns were obtained and analyzed. Using Cu-K_{α} radiation XRD study was done on the x-ray diffractometer (make: Bruker D2 Phaser). 2θ angles were taken from 20-90°. The XRD pattern was compared with JCPDS files to identify various x-ray peaks obtained. Specimens were square, having 1mm thickness for the XRD test.

4.5.3 Hardness Study

Rockwell hardness test was conducted to measure the bulk hardness of nitrided and non-nitrided specimens. Diamond cone indenter was used to measure the hardness on the C scale with load 150g with dwell time 10 s. Five readings were taken at the surface of nitrided and non-nitrided specimens, and their average was reported as the surface hardness. All the hardness readings were taken at room temperature. Hardness measurement carried out as per ASTM E18-05 standard.

4.5.4 Surface Roughness Study

The surface roughness of the specimen was measured using a 2D stylus type contact surface profilometer (Make: Taylor and Hobson, 315). Four readings were taken at the surface of nitrided and non-nitrided specimens, and their average was reported as the surface roughness R_a .

4.5.5 Field emission Scanning Electron Microscopy (FE-SEM) Study

The mounted samples were studied on FE-SEM (SEM, make: JEOL JSM-7610FPlus) by secondary electron imaging and backscattered imaging. Surface and coating morphology of specimens and phase present were studied. Energy dispersive

spectroscopy (EDS) analysis with SEM was also done to know about the variation in the concentration of alloying elements through the nitride layer.

4.5.6 Tribological analysis

Contact type stylus profilometer is used to study the topological features of the wear profile, and volume loss was calculated by measuring the surface profiles of the wear scar. The measurements were done across the track at four different locations. The average cross-sectional area of the wear scar has multiplied to its length to obtain the volume loss due to wear. Specific wear rate (W_{sp} ,(mm^3/Nm)) was determined using the following relation between volume loss (V_L ,(mm^3)) applied load (P,(N)), and sliding distance (L,(m)):

$$\mathbf{W}_{sp} = \frac{\mathbf{V}_{L}}{\mathbf{P} * \mathbf{L}}$$

A field emission scanning electron microscope (FE-SEM) of (SEM, make: JEOL JSM-7610FPlus) is used to observe topological feathers of the wear track. The basic working of SEM is the scanning of the specimen using a focused beam of electrons that are produced in an electron gun using the high electric field. Secondary electron scanning mode at a 5KV electron beam is used to detect the microstructure. These secondary electrons that are generated from the sample due to striking off the surface electrons with the electron beam give an image with a proper resolution of the topography of the sample.

Chapter 5

5.1 Result and Discussions of AISI H13 Tool Steel

5.1.1 Microstructure

Figure 11 shows the microstructure of as-received and plasma nitrided AISI H13 tool steel at the cross-section of specimens.



Figure 9: Optical Micrograph of the cross-section of (a) asreceived and (b) plasma nitrided AISI H13 Tool Steel.

After plasma-nitriding, the ingress of nitrogen promotes significant microstructural modifications in the near-surface region. Optical image of the nitride specimen revealed two distinct layers. The uppermost layer is a compound layer or white layer or nitride layer, and below it, there is a modified region known as the diffusion layer [44]. The microstructure shows the presence of the nitride layer. The observed thickness of nitrided white layer is about 14.8 (± 1.2) µm shown in Figure 11. The morphology of nitride white layer near-surface was needle-like fine precipitates in the martensite matrix [41].

5.1.2 Surface Roughness

The surface roughness of the as-received and plasma-nitrided surface of the AISI H13 tool steel was studied using a 2D stylus contact-type surface profilometer. Figure 12 shows the roughness profile of the as-received and plasma-nitride specimen.



Figure 10: Surface roughness profile of (a) plasma-nitride and (b) as-received specimens.

The average surface roughness R_a of the as-received specimen is 0.0248 µm. However, R_a increases to is 0.1412 µm after plasma-nitrided. Higher R_a value in case of plasma-nitrided specimen is due to plasma species bombardment as a consequence of the sputtering effect [45], [34].

5.1.3 XRD

The XRD diffractograms of as-received and plasma-nitride specimens on the AISI H13 tool steel are shown in Figure 13(a).



Figure 11: X-ray diffraction pattern and (b) hardness variation of as-received and plasma-nitrided specimens.

The diffraction pattern of the untreated samples shows the peak of α -Fe phase only. It can be seen from Figure 13 (a) that the nitride layer consists of Fe₄N, Fe₃N, Cr₂N, and CrN phases in plasma-nitrided sample. The CrN may be the first phase that is formed during the plasma nitriding of the AISI H13 tool steel. The precipitates of Fe₃N follows the amount of diffused nitrogen increases. That is because Cr has a higher affinity to nitrogen rather than Fe resulting in the more natural formation of CrN than Fe₃N and Fe₄N.

5.1.4 Hardness

Rockwell hardness measurement using C scale was carried out on as-received and plasma-nitrided samples. The applied load for the measurements was 150g. As-received material shows the hardness of 43.26 (\pm 1.36) HRC. However, it reached to $68.54 (\pm 1.78)$ HRC after plasma nitriding (Figure 13 (b)). The increase in surface hardness might be due to the presence of nitrides of iron. The surface hardening is well established due to the precipitation of nitrides and to the supersaturation with the nitrogen of the bcc matrix in diffusion zone [41].



5.1.5 Dry Sliding Wear Test

Figure 12: Variation of volume loss of the as-received and plasma nitrided specimen at 15N, 25N, and 35N loads with (a) 0.3 m/s and (b) 0.5 m/s sliding velocity

Figure 14 (a) and (b) shows the variation of volume loss for different loading conditions at various sliding speed for the as-received and plasma-nitride specimens. The plasmanitrided specimen shows a drastic reduction in volume loss than the non-treated specimens in all loading and operating conditions. This drastic reduction in the volume loss is due to the improved hardness after plasma-nitriding. This enhancement in surface hardness is due to the presence of hard and brittle Fe₃N phase. The volume loss of the as-received and plasma-nitrided specimen increases with increase in applied load at both the sliding velocities except for 35 N load at 0.3 m/s velocity (Figure 14 (a) and (b)). At 0.3 m/s sliding velocity and 35 N load, the as-received specimen strain hardened due to high load and lower sliding velocity which subsequently reduce volume loss than 25 N load. The maximum reduction in volume loss after plasma nitriding is about 97% at 0.3 m/s sliding velocity and 25 N load. However, 98.33% improvement is observed at 0.5 m/s sliding velocity and 15 N load after plasma nitriding of H13 steel (Figure 14 (a) and (b)).

Fig. 15 (a) and (b) shows the variation in the specific wear rate with different loading conditions at a particular sliding speed for the as-received and plasma-nitride specimens. The specific wear rate of plasma nitrided steel is less than as-received specimen for all load and sliding velocity.



Figure 13: Comparision of specific wear rate of the asreceived and plasma nitrided specimen at 15 N, 25 N, and 35 N loads with (a) 0.3 m/s and (b) 0.5 m/s sliding velocity.

At 0.3 m/s sliding velocity, lowest specific wear rate of plasma nitrided specimen is observed at 35 N load. The specific wear rate for the as-received specimens decreases with an increase in load at 0.5 m/s sliding velocity. However, plasma-nitrided specimen shows the reverse trend, as shown in Figure 15 (b). Figure 16 shows the variation of coefficient of friction (COF) with time at 15N, 25N, and 35N normal load. and 0.3m/s and 0.5m/s sliding speed for the non-treated and plasmanitrided specimens in dry sliding conditions. At 15 N load, the COF of nitrided steel is higher at lower sliding velocity and lower at higher sliding velocity. The COF at 25 N load, shows almost similar trend for as-received and plasma-nitrided specimens (Figure 16 (b & e)). However, at the 35 N load and both sliding velocities, as-received specimen shows the higher COF than the plasma-nitrided specimen, as shown in Figure 16 (c & f). The fluctuation in the profile of COF is due to the presence of debris particles because COF value is strongly depends on surface cleaning state i.e. tribological film during the wear test [40].



Figure 14: Variation of coefficient of friction (CoF) of the asreceived and plasma-nitrided specimen at (a-b) 15 N, (c-d) 25 N, and (e-f) 35 N loads with (a-c-e) 0.3 m/s, and (d-e-f) 0.5 m/s sliding velocity in dry condition.

Figure 17 and 18, shows the variation of average COF with 15N, 25N, and 35N normal load at 0.3m/s and 0.5m/s sliding speed for the non-treated and plasma-nitrided specimens in dry sliding conditions respectively. The average COF for the asreceived specimen increases with an increase in load at 0.3 m/s sliding velocity, (Fig. 17). However, COF of plasma-nitrided specimens increases slightly at 25 N load and then decreases at 35 N compared to lower loading conditions. At higher sliding velocity (0.5 m/s), the nontreated specimen shows lower COF

at 25 N load and plasma nitrided specimen shows similar trend as that of 0.3 m/s sliding velocity.



Figure 16: Variation of the coefficient of friction (CoF) of the as-received and plasma-nitrided specimen at 15 N, 25 N, and 35 N loads with 0.3 m/s sliding velocity.



Figure 15: Variation of the coefficient of friction (CoF) of the as-received and plasma-nitrided specimen at 15 N, 25 N, and 35 N loads with 0.5 m/s sliding velocity.

5.1.6 Wear Mechanism

The SEM analysis is performed on the worn-out surfaces as it provides insight into the underlying macroscopic deformation mechanism during wear. The representative SEM images of worn surfaces are shown in Figure 19 and 20 for 15 N, 25 N, and 35 N loading conditions of as-received and plasma nitrided specimens at 0.3 m/s and 0.5 m/s sliding speed, respectively.

At 0.3 m/s sliding velocity, non-treated specimens show plowing and scratching wear at lower loading conditions (15 N). However, micro-cutting and adhesion wear is observed at 25 N and 35 N loads respectively (Figure 19 (a, c and e)). In plasma-nitrided samples smooth wear track is observed at 15 N load. As the load increases, few wear debris are observed on the smooth wear tracks (Figure 19 (b, d and f)). These observed particles are formed due to the breakage of asperity present on to the surface.

At the higher sliding speed, fatigue and delamination wear is observed in non-treated specimen, as shown in Figure 20 (a-c-e). In plasma-nitrided specimens scratching is observed at 0.5 m/s sliding velocity, shown in Figure 20 (b-df). For 15 N load micro-cutting is observed with few scratches. As load increases, the more severe scratching is observed with small amount of wear debris on wear tracks of plasma nitrided specimen. The presence of hard and brittle Fe₃N phase intensifies the scratching of the nitride layer.



Figure 17: SEM micrograph of the wear-track of (a-c-e) asreceived, and (b-d-f) plasma-nitrided specimens treated at (ab) 15 N, (c-d) 25 N, and (e-f) 35 N loads with 0.3 m/s sliding velocity in dry condition.



Figure 18: SEM micrograph of the wear-track of (a-c-e) asreceived, and (b-d-f) plasma-nitrided specimens treated at (ab) 15 N, (c-d) 25 N, and (e-f) 35 N loads with 0.5 m/s sliding velocity in dry condition.

5.2 Result and Discussions of AISI 2205 Duplex Stainless Steel

5.2.1 Microstructure

Figure 5.21 shows the SEM and optical micrographs at the cross-sections of the (a) untreated, (b) SMATed, (c) plasmanitrided, and (d) plasma-nitrided after SMAT of the duplex stainless steel (DSS).



Figure 19: SEM micrograph of the cross-section of (a) asreceived, (b) SMATed, (d) Nitrided after SMAT, and (c) optical micrograph of the nitrided specimen.

Figure 5.21 (a) shows the traditional duplex stainless-steel structure in which the elongate austenite (Y) are dispersed in the ferrite (α) matrix. Rapid hardening in the austenite (Y) grain near the surface region than the ferrite grains (α) after SMAT is attributed due to planer dislocation movement causing the accumulation of the mechanical twins are present in the austenite (Y) grains near the surface region as shown in Figure 5.21 (b). [46].

Evolution of more intense nitride layer in the ferrite (α) phase than the austenite (Y) phase is observed in the plasma-nitrided specimen due to the more affinity of nitrogen towards the ferrite (α) phase and more preferential sites to the formation of iron nitrides than the austenite (Y) phase [42], [47], [48], shown in Figure 5.21 (c). The increase in the diffusion of nitrogen after SMAT is observed in the duplex treated i.e. plasma-nitriding after SMAT specimen due to the higher availability of dislocations which provides the extra pathway to nitrogen and showing the similar sequence towards the ferrite (α) and austenite (Y) phase to that of non-SMATed specimen, shown in Figure 5.21 (d) [4], [16], [48], [36].

5.2.2 XRD

The XRD diffractograms of as-received, SMATed, and plasmanitride specimens on the AISI 2205 duplex stainless steel are shown in Figure 22. Both, as-received and SMATed specimen shows ferritic and austenitic phase peaks but the SMATed specimen shows relative decrement in peak intensity of austenitic phase whereas, the increment in peak intensity of ferritic phase. This observation indicates the refinement of grains at the surface and increase in dislocation density after SMAT [21].In the untreated sample ferritic and austenitic phases are dominant whereas after nitriding the intensity of ferrite peak has decreased. However, diffraction pattern indicates the presence of CrN, Cr_2N , expanded austenite and Fe₃N phases in the nitrided specimen [16], [49], [50].


Figure 20: X-ray diffraction pattern of as-received, SMATed, and plasma-nitrided specimens.

5.2.3 Dry Sliding Wear Test

Figure 23 and Figure 24 shows the variation of volume loss with 10 N and 20 N normal load at 0.5 m/s and 1 m/s sliding speed for the non-treated, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimens. The as-received specimen shows the higher volume loss, whereas plasmanitrided specimen after SMAT shows the lowest volume loss at corresponding loading and sliding condition. The plasmanitrided specimen after SMAT shows maximum reduction in volume loss is about 96% at 0.5 m/s sliding velocity and 10 N load, whereas, for nitrided and SMATed specimens, maximum reduction in volume loss is about 93% and 49% respectively at 0.5 m/s sliding velocity and 10 N load (Figure 23).



Figure 21: Variation of volume loss of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 10 N and 20 N loads with 0.5 m/s sliding velocity.

However, at 1 m/s sliding speed, plasma-nitrided specimen after SMAT shows maximum reduction in volume loss is about 93% at 10 N load whereas, for nitrided and SMATed specimens, maximum reduction in volume loss is about 92% and 42% respectively at 1 m/s sliding velocity and 10 N load (Figure 24). This reduction in volume loss is due to the improved hardness of the top surfaces of the specimen.



Figure 22: Variation of volume loss of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 10 N and 20 N loads with 1 m/s sliding velocity.

Figure 25 and 26 shows the comparison of a specific wear rate with 10N and 20N normal load at 0.5m/s and 1m/s sliding speed for the non-treated, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimens. For all the loading and sliding conditions, the as-received specimen shows the maximum specific wear rate, whereas plasma-nitrided specimen after SMAT shows the minimun specific wear rate at corresponding loading and sliding conditions. This variation of specific wear rate is due to the effect of an increase in surface micro-hardness and formation of the wear-resistant hard surface.



Figure 23: Comparision of specific wear rate of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 10 N and 20 N loads with 0.5 m/s sliding velocity.



Figure 24: Comparision of specific wear rate of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 10 N and 20 N loads with 1 m/s sliding velocity.



Figure 25: Variation of the average coefficient of friction (COF) of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 0.5 m/s and 1 m/s sliding velocity with 10 N load.



Figure 28: Variation of the average coefficient of friction (COF) of the as-received, SMATed, plasma-nitrided, and plasma-nitrided after SMAT specimen at 0.5 m/s and 1 m/s sliding velocity with 20 N load.

Figure 27 and 28, shows the variation of average COF with 10N and 20N load at 0.5m/s and 1m/s sliding speed for as received, SMATed, plasma-nitrided and plasma-nitrided after

SMAT specimens, respectively. The average COF is increases with increase in the sliding speed at 20N load for as-received, SMATed and plasma-nitrided after SMAT specimen (Figure 28). However, at 10N load average COF is decreases with increase sliding speed for all specimen conditions (Figure 27).

5.2.4 Wear Mechanism

The SEM analysis is performed on the worn-out surfaces as it provides insight into the underlying macroscopic deformation mechanism during wear. The representative SEM images of worn surfaces are shown in Figure 29, for 10N and 20N normal load at 0.5m/s and 1m/s sliding speed for the non-treated, SMATed, specimens of AISI 2205 DSS, respectively. Micrograph of wear track for SMATed specimen shows microcutting, and delamination at 10N load whereas fatigue phenomenon at 20N load. However, for non-SMATed specimen ploughed grooves at 10N load whereas adhesion and micro-cutting at 20N is observed.



Figure 29: SEM micrograph of the wear-track of (a-c) asreceived, and (b-d) SMATed specimens treated at (a-b) 10 N, and (c-d) 20 N loads with 0.5 m/s sliding velocity.

Chapter 6

Conclusion

In this study, plasma-nitriding was carried out on hot formed AISI H13 tool steel. The aim is to develop a hard and wear resistant surface. The effect of developed nitrided layer on the surface hardness and tribological behaviour were investigated for AISI H13 tool steel along with this surface mechanical attrition treatment (SMAT) and subsequently, plasma nitriding was utilized to enhance the surface properties of AISI 2205 Duplex Stainless Steel. Dry sliding wear tests were carried out on both materials in a pin on disc tribometer with α -Al₂O₃ ball as counter body. Specimens were investigated in this work using optical microscope, scanning electron microscope (SEM)), X-ray diffraction (XRD), and hardness measurements.

- Ingress in the nitrogen after plasma-nitriding promotes significant modification of microstructure and surface hardness in the near-surface region was observed for AISI H13 tool steel and AISI 2205 DSS.
- The maximum reduction in volume loss after plasma nitriding is about 97% at 0.3 m/s sliding velocity and 25 N load. However, at higher loading condition untreated specimen shows the higher COF than the plasma-nitrided specimen due to higher surface roughness for AISI H13 tool steel.
- The untreated specimen shows abrasive and adhesive phenomenon, whereas for all plasma-nitrided samples, scratching and micro-cutting was observed at various loading and sliding conditions for AISI H13 tool steel.
- The increase in the diffusion of nitrogen after SMAT was observed in the duplex treated i.e. plasma-nitriding after SMAT specimen due to refined grains at the surface which

provides the extra pathway to nitrogen to diffuse for AISI 2205 Duplex Stainless-steel.

• The AISI 2205 DSS plasma-nitrided specimen after SMAT shows maximum reduction in volume loss is about 96% at 0.5 m/s sliding velocity and 10 N load. However, at 1 m/s sliding speed, plasma-nitrided specimen after SMAT shows maximum reduction in volume loss is about 93% at 10 N load.

Chapter 7

Future Scope of the Study

As discussed, earlier SMAT and plasma-nitriding are very popular method to improve the mechanical properties of the surface. The response of SMAT on duplex stainless steel and its effect on tribology is having a large area of research. Along with this the tribological and deformation behaviour of tool steel at high temperature having a scope of research.

Chapter 8

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