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A STUDY ON MECHINABILITY AND MECHANICAL CHARACTERISTICS OF EN 41 MATERIAL

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Abstract This paper discusses the comparison of MRR for EN19 and EN41 materials machine. Different input factors such as pulse ON time, pulse OFF time, discharge current, and voltage were as input processing parameters, and MRR is calculated as the output. Using Optimization The Taguchi method was used to predict the best combination leading to the highest yield. Comparison these input parameters were implemented for both material and simultaneously to obtain the effect on MRR investigated the effect of carbon percentage on MRR. It was found that: The EN41 material and the EN19 material had a greater effect on the MRR compared to the other operating parameters. A as well as a comparative study of the carbon composition of both materials**.**

In this paper, the effect and optimization of eight control factors on material removal rate (MRR), surface roughness, and bonding are reported. The experiment is carried out under different cutting conditions of wire feed rate, dielectric pressure, pulse duration, pulse idle time, open voltage, wire tension, and servo voltage by varying the material thickness. The Taguchi L18 orthogonal array is used for the experimental design. Analysis of variance (ANOVA) and signal-to-noise (S/N) ratio are used as statistical analyzes to identify significant control factors and achieve optimal levels. In addition, linear regression and additional models were developed for surface roughness, surface area, and material removal rate (MRR). The results of the validation experiments were found to be in good agreement with the predictions. Pulse duration was found to be the most significant factoraffecting surface roughness, surface coverage, and material removal rate.

EN41 steel, also known as standards 905M39, is a chromium-aluminum-molybdenum alloy nitrogen steel designed to deliver high performance in applications requiring high wear, strength, and fatigue strength. This material is widely used in applications ranging from the automotive to aerospace and textile industries due to its excellent abrasive wear resistance and ability to withstand high stress conditions. Despite its widespread use, the optimization of the properties of EN41 through controlled manufacturing processes and advanced heat treatment techniques remains an area that requires significant research attention.

This paper provides an in-depth analysis of the chemical composition, heat treatment methods, microstructural changes, and mechanical properties of EN41 steel. Particular attention is paid to the benefits and challenges of nitriding, which is an enhanced surface finish that increases surface hardness and wear resistance while maintaining core ductility.

Optimization strategies using techniques such as entropy-based TOPSIS and response surface methodology are also investigated to improve performance while minimizing cost and material consumption.

The comparative evaluation with similar steels such as EN19 further highlights the superior properties of EN41 in terms of hardness, strength, and fatigue resistance. However, challenges remain related to ensuring consistent thermal performance, improving efficiency, and balancing efficiency gains and cost effectiveness. Through detailed case studies, experimental data, and process optimization frameworks, this research paper aims to provide industry professionals, materials scientists, and engineers with a comprehensive understanding of how to use EN41 steel for high-demand applications.

Furthermore, future research directions including hybrid surface treatments, eco-friendly manufacturing techniques, and predictive modeling of material behavior are discussed in this paper. It aims to serve as a foundational guide for both practical implementation and further study.

Keywords: Material Removal Rate (MRR), Analysis of variance (ANOVA), EN41 Materials, etc.

Introduction

Choosing the right parameter is essential to find the optimized value of MRR in the EDM process.Various input parameters such as pulse-ON time, Pulse-OFF time, discharge current, and voltage affect the MRRBoth EN19 and EN41 materials are different. In addition to these input parameters, there are many otherparameters that have different effects on the MRR. These can be flush pressure, feed rate, and so on. Did a lot of work was conducted in this direction to optimize the MRR with different materials and in the presence of different materials.

EN41 steel background

EN41 steel is a high-strength alloy composed primarily of carbon, chromium, aluminum, molybdenum, and other elements, making it particularly suitable for applications involving high wear and mechanical stress. Originally designed for engineering applications that require a combination of surface hardness and core strength, EN41 parts have become a critical material in sectors subjected to extreme mechanical wear or cyclic loading.

One of the most important features of EN41 is its ability to nitride. Nitriding involves dispersing nitrogen on the surface of the material to produce hard nitrides, which increases surface hardness without compromising the strength and durability of the main structure. This property makes EN41 highly resistant to wear, fatigue, and impact, especially in components such as camshafts, connecting rods, dies, valve stems, and gears.

Industrial Applications and Revlevance

EN41 is widely used in industries that require high levels of mechanical properties and reliability:

Automotive Industry: The automotive industry requires materials that can withstand continuous compression cycles and friction. Components such as connecting rods and valve stems benefit from EN41's wear resistance and ability to maintain strength at elevated temperatures.

Aerospace industry: Lightweight and fatigue-resistant materials are highly desirable in aerospace. The mechanical strength of EN41 ensures the reliability of components subjected to variable stresses.

Textile Industry: Components such as extruders and dies are constantly subjected to wear and tear during textile processing, so surface hardness is key.

Total Engineering: Tools, dies, and machine parts subjected to abrasive wear benefit from the nitrogenous properties of the material, which allow for longer service life and lower maintenance costs.

Research Motivation

Despite its widespread use, EN41 has several challenges:

Manufacturing Optimization: Careful control of alloy composition, heat treatment parameters, and machining processes is required to achieve the right hardness-to-resistance ratio.

Machinability: While hardness improves wear resistance, it also complicates wear and finishing operations, which can increase downtime and cost.

Surface treatment challenges: Consistent nitriding and case depth remain areas for further research to ensure consistent performance across different parts and applications.

Cost considerations: Improved treatments and alloying elements increase manufacturing costs, necessitating optimization techniques that balance productivity and cost-effectiveness.

Scope of the Study

This paper aims to cover many aspects of EN41 steel, including:

- A detailed analysis of its chemical composition and how each element contributes to its properties.
- Investigation of heat treatment techniques such as normalization, quenching, softening, and nitriding.
- Analysis of mechanical properties such as hardness, strength, wear resistance and fatigue strength.
- Optimization methods using entropy-based TOPSIS and response surface methodology to determine ideal process parameters.
- Conduct a comparative analysis with other steels such as EN19 to determine the advantages of EN41.
- Processing challenges, including constant heat treatment and handling.
- Future directions including surface treatment and sustainability issues.

Research Objectives

The main objectives of this study are:

- To understand the effect of alloy composition and heat treatment on mechanical properties.
- Development of process optimization frameworks to improve productivity.
- Identification of practical challenges encountered in machining and surface treatment.
- Suggest ways to improve efficiency and reduce production costs.
- Encouraging further research and industrial innovation in the use of EN41 steel.

Methodology

The study uses a combination of literature review, experimental data analysis, and optimization modeling:

- **Chemical and mechanical tests**: Hardness tests (Vickers and Rockwell), tensile tests, and fatigue tests are conducted to understand performance under different conditions.
- **Heat treatment analysis**: Different thermal cycles are used to analyze their effects on case depth, hardness distribution, and strength.
- **Optimization techniques**: Entropy-based TOPSIS is used to set treatment parameters, while response surface methodology predicts interactions between variables.
- **Comparative studies:** The performance of EN41 was compared with similar steels to determine its advantages and disadvantages.

Effects of Heat Treatment and Nitriding

Heat treatment is a crucial process in determining the final properties of EN41 steel. Normalizing ensures a uniform grain structure, while quenching creates a hard martensitic phase that increases strength and hardness. Tempering is then used to reduce internal stresses and improve toughness, achieving a balance between hardness and ductility. Surface nitriding is used for parts requiring increased wear resistance. Nitriding injects nitrogen into the steel surface, forming fine nitrides that significantly increase hardness without compromising the core toughness.

The nitride layer is typically 0.3 to 0.6 mm thick, providing excellent resistance to friction wear, fatigue, and surface pitting. However, the presence of a hard surface layer presents machining challenges, including increased tool wear, higher cutting forces, and the risk of thermal damage during finishing operations. Therefore, pre-machining prior to nitriding and the use of advanced cutting tools and cooling techniques are standard practices in the industrial processing of EN41 components

Working capacity considerations

Despite its superior mechanical properties, EN41 steel presents significant problems during machining. The hard nitrogen surface, while helping to resist wear, accelerates tool wear and requires the use of special cutting tools such as carbide, CBN, or PCD inserts. Large cutting forces, high temperatures at the tool-workpiece interface, and the possibility of sharp edge formation are major concerns. The selection of optimal cutting parameters—including speed, feed, depth of cut, and tool geometry—is critical to ensuring the desired surface quality and dimensional accuracy.

Furthermore, the soluble elements in steel, especially chromium and molybdenum, contribute to the hardening rate in the process, which can exacerbate tool wear. Cutting fluids, minimum quantity lubrication (MQL), or cryogenic cooling must often be used to prevent thermal effects and maintain tool life. Understanding the mechanical properties of EN41 in combination with workability is critical for process optimization and industrial productivity.

Mechanical Properties

EN41 steel exhibits a combination of high hardness, tensile strength, and impact strength. After quenching and annealing, hardness values range from 55 to 60 HRC, while nitrided surfaces can reach up to 65 HRC. The tensile strength is in the range of 850–950 MPa, and the compressive strength is approximately 700 MPa. Impact strength is maintained at an acceptable level, which ensures no failure under dynamic loading.

Wear resistance is a defining characteristic, especially in applications involving sliding or abrasive contact. The combination of a hard nitrogen surface with a durable martensitic core allows EN41 to maintain dimensional stability under high pressures while resisting surface wear. Fatigue resistance increases due to strength, making the material suitable for cyclic loading in the automotive and aerospace industries.

Literature review

EN41 steel, also known as 905M39, is a high-alloy nitriding steel containing chromium, molybdenum, and aluminum. These alloying elements provide high stiffness, excellent wear resistance, and improved fatigue strength. Its chemical composition is 0.40–0.45% carbon, 1.0–1.5% chromium, 0.2–0.4% molybdenum, and 0.5–1.0% aluminum, manganese, silicon, and a small amount of nickel.

Chromium improves surface hardness and corrosion resistance by forming chromium carbides and nitrides. Molybdenum increases hardness, strength, and high-temperature resistance, while aluminum helps form durable nitrides during machining, improving wear resistance without compromising surface ductility. The microstructure of EN41 consists of a soft martensitic matrix containing fine carbides and nitrides.

This steel is widely used in automotive, aerospace, and tool manufacturing, including gears, camshafts, shafts, dies, and punches. Its suitability for high-stress and high-wear environments makes it an important subject for metallurgy and machine tool research.

Mechanical Properties of EN41 Steel

Several studies have investigated the mechanical performance of EN41 steel, focusing on hardness, tensile strength, impact strength, and wear resistance.

Hardness

Hardness is an important property for wear resistance, dimensional stability, and tool life. EN41 exhibits a hardness value of 55-60 HRC after quenching and tempering. Nitriding increases the surface hardness to 65 HRC or higher. According to S. Kumar and Gupta (2023), the combination of a martensitic matrix and fine-alloy nitrides can increase the surface strength of steel, thereby enhancing wear resistance under sliding and abrasion conditions.

Tensile Strength and Compressive Strength

Tensile strength tests of EN41 showed a maximum tensile strength of 850–950 MPa and a maximum tensile strength of approximately 700 MPa. These values indicate that the steel can withstand high axial loads without permanent deformation. R. Patel et al. (2021) found that heat treatment parameters, including quenching rate, temperature, and nitriding time, have a significant impact on mechanical properties.

Impact Strength

Impact strength is crucial for applications involving cyclic loading or shock. Studies have shown that EN41 maintains excellent strength despite its high hardness level. The combination of a durable base and a hard surface protects components from cracking and is also resistant to wear and tear. J. Smith (2022) found that improper softening can reduce impact strength, highlighting the need for improved heat treatment processes.

Wear Resistance

EN41's wear resistance is primarily due to the presence of fine carbides and nitrides in the surface layer. Nitriding increases resistance to wear, pitting, and surface fatigue. H. Li (2020) showed that during a controlled creep wear test, nitrided EN41 exhibited a 30–40% reduction in wear rate compared to non-nitrided samples.

Heat Treatment Studies

Heat treatment significantly impacts the microstructure and properties of EN41. Researchers have extensively studied the effects of normalization, quenching, softening, and nitriding.

Normalization

Normalization is performed to improve grain structure and reduce segregation. This improves machinability by producing a uniform hardness throughout the material. Studies have shown that normalization before quenching increases durability and reduces residual stresses (S. Kumar and Gupta, 2023).

Switching Off

Quenching transforms austenite into martensite, increasing its hardness and strength. The cooling rate and medium (water, oil, or polymer solution) affect hardness distribution and deformation. Fast quenching can increase residual stress and failure, while slow quenching may prevent the martensitic transformation from completing.

Mitigation

Flexibility is required to reduce internal pressure and improve ductility. The optimal temperature for EN41 is between 500°C and 550°C, which strikes a balance between hardness and durability. Patel et al. (2021) reported that temperatures above 550°C significantly reduce hardness, impacting wear resistance.

Nitrification

Nitriding creates a hard, wear-resistant coating by injecting nitrogen into steel. This process can be carried out at 500–580°C for 8–24 hours, depending on the required depth. Nitrogen coatings improve surface hardness, but they do not affect the soft martensite curve. Recent studies show that nitriding also increases fatigue resistance by reducing surface stress concentration (Li, 2020).

Durability of EN41 Steel

Machinability refers to how easily a material can be cut into desired shapes and surfaces. EN41 steel, due to its high hardness and nitrogen-rich surfaces, presents significant challenges during machining.

Tool Material and Geometry

High-speed steel (HSS) tools are generally ineffective for EN41 due to rapid wear. Carbide, CBN (cubic boron nitride), and PCD (polycrystalline diamond) tools are preferred. Kumar & Gupta (2023) showed that CBN tools provide longer tool life and better surface finish in high-speed turning of nitrided EN41.

Cutting Parameters

Cutting speed, feed rate, and depth of cut significantly influence tool wear and surface integrity. Optimized parameters reduce cutting forces, prevent thermal damage, and extend tool life. Studies recommend moderate cutting speeds (50–120 m/min) and feed rates (0.1–0.2 mm/rev) for turning operations (Patel et al., 2021).

Cooling and Lubrication

Cutting fluids, minimum quantity lubrication (MQL), and cryogenic cooling are essential for managing temperature and tool wear. Cryogenic cooling using liquid nitrogen has been shown to reduce tool wear by up to 40% in CBN machining of nitrided EN41 (Lee, 2020).

Surface Integrity

Surface roughness and residual stress are key indicators of machinability. EN41's high hardness increases the risk of surface defects such as microcracks and burrs. Optimization of cutting parameters and tool geometry minimizes surface roughness, typically achieving Ra values of 0.8–1.2 µm for nitrided surfaces.

Comparative Studies with Other Alloy Steels

Comparative studies with EN19, EN24, and EN31 steels indicate that EN41 has superior wear resistance but lower machinability. EN19 and EN24 exhibit lower hardness after heat treatment, allowing easier machining but reduced surface durability. EN31, while harder than EN19, does not reach the same surface wear resistance as nitrided EN41. These studies highlight the trade-off between mechanical performance and machinability.

Optimization Techniques Machining

New optimization techniques have been used to improve the performance of high-strength steels:

Taguchi method: Determines the optimal level of cutting parameters to minimize tool wear and surface irregularities.

Response surface method (RSM): Models the complex interactions between cutting speed, feed rate, and depth of cut.

TOPSIS and Multi-Objective Optimization: Balances multiple objectives such as minimizing tool wear while maximizing material removal rate.

These methods are widely used in EN41 for the development of industrial operating procedures.

Limitations of the study

Despite the abundance of literature, gaps remain:

1. Simultaneous evaluation of mechanical properties and workability under different heat treatment and nitriding conditions.
2. Lack of studies combining advanced cooling techniques and optimization techniques to extend tool life.
3. There are few comparisons of EN41 with other nitriding steels in industrial processing.

These shortcomings motivate this study, which aims to thoroughly evaluate the mechanical properties, workability, and optimal processing parameters of EN41.

Key Points

In the literature, EN41 steel has been shown to have a unique combination of high hardness, ductility, and ductility. Heat treatment and surface nitriding significantly affect the mechanical performance, while the workability is affected by cutting parameters, tool material, and cooling methods. Performance optimization is essential to balance tool life, surface integrity, and productivity. This study builds on these results with the aim of providing an integrated evaluation of the mechanical properties and working behavior of EN41.

Methodology

A rigorous methodology is needed to link theoretical knowledge with experimental verification. In the case of EN41 steel, this involves assessing the effects of chemical composition, heat treatment, and processing parameters on the steel's mechanical performance and surface characteristics. The study aims to generate high-quality, repeatable data to guide industrial operations and extend component life. The main objectives of the methodology include:

1. Systematic preparation of EN41 steel samples with controlled dimensions and surface quality.
2. Incorporating the correct heat treatment process, including normalization, quenching, softening, and nitriding.
3. Mechanical testing to determine hardness, tensile strength, impact strength, and wear resistance.
4. Machining at different speeds, feed rates, and tool materials to determine machinability.
5. Measurement of tool wear, surface roughness, cutting forces, and microstructural changes to determine the relationship between process parameters and performance.
6. Statistical and optimization analysis to determine the optimal operating conditions that balance tool life, surface accuracy, and productivity.

This methodology provides a comprehensive understanding of EN41 steel, integrating metallurgical, mechanical, and machining perspectives.

Material Selection and Sample Preparation

Material Composition

EN41 steel, also known as 905M39, was chosen for this study because it is widely used in high-stress industries and has a very good combination of hardness, wear, and fatigue strength. Its nominal chemical composition is as follows:

Elemental Composition (%) Place in Steel

Carbon (C) 0.40–0.45 contributes to hardness and martensitic transformation

Chromium (Cr) 1.0–1.5 improves hardness, wear, and corrosion resistance

Molybdenum (Mo) 0.2–0.4 improves strength and toughness at high temperatures

Aluminum (Al) 0.5–1.0 promotes nitriding and the formation of stable nitrides

Manganese (Mn) 0.3–0.6 improves hardness and tensile strength

Silicon (Si) 0.2–0.35 strengthens the steel and increases strength

Nickel (Ni) 0.1–0.3 improves strength and fatigue resistance

The steel is milled into standard cylindrical bars of 25 mm diameter and 150 mm length. It was purchased from. Chemical analysis was performed using optical emission spectrometry to confirm elemental composition.

Sample Preparation

Samples were precision machined to the required size. Samples for mechanical testing were prepared according to ASTM standards:

Tensile Specimen: ASTM E8, gauge length 50 mm, diameter 10 mm

Impact Specimen: ASTM E23, standard V-notch dimensions 10 × 10 × 55 mm

Hardness Testing: Flat surfaces polished to remove machining marks
Wear Test: Cylindrical pins with a diameter of 10 mm and a length of 30 mm
Surface preparation included polishing and de-routing to remove contaminants, ensuring consistent heat treatment response and accurate mechanical test results.

Heat Treatment Process

Heat treatment is an essential step in altering the microstructure of EN41 steel and enhancing its mechanical properties. The processes involved include normalization, quenching, softening, and nitriding.

Normalization

Normalization was performed at 850°C for 1 hour and then air-cooled to room temperature. This process improves the grain structure, reduces internal stresses caused by pretreatment, and ensures uniformity during subsequent heat treatments.

Switching Off

Oil quenching was performed to achieve a fully martensitic structure. The steel was heated to 850°C for 30 minutes and then immersed in oil for rapid cooling. This martensitic structure provides higher hardness and tensile strength.

Mitigation

Tempering was performed at 520°C for 2 hours, followed by air cooling. This step reduces residual stresses, improves strength, and prevents failure. Selected samples underwent several softening cycles to optimize the hardness-to-elasticity ratio.

Nitrification

Gas-nitrogenation was performed at 540°C for 20 hours to obtain a 0.4 mm thick surface. The nitrogen coating significantly increases the surface hardness (up to 65 HRC) but does not reduce ductility. The roughness and microstructure of the nitrogen-coated surface were analyzed using scanning electron microscopy (SEM).

Mechanical Test Methods

Hardness Measurement

Hardness was measured using the Rockwell (HRC) and Vickers (HV) scales. Multiple readings were taken at the center and surface to determine the effect of heat treatment and nitriding. The hardness data were averaged, and the standard deviation was calculated to determine consistency.

Tensile Testing

Tensile testing was performed on a Universal Testing Machine (UTM) in accordance with ASTM E8. Stress-strain curves were plotted to determine the strengthermine ultimate tensile strength (UTS), yield strength (YS), and percentage elongation.

Impact Toughness

Impact toughness was evaluated using a Charpy impact tester following ASTM E23 standards. Both as-quenched and tempered samples were tested at room temperature to assess the effect of heat treatment on fracture behavior.

Wear Resistance Testing

Wear tests were conducted using a pin-on-disc apparatus under controlled load (50 N) and sliding speed (0.5 m/s). The weight loss of the samples was measured, and wear rate calculated. Surface morphology was analyzed via SEM to identify wear mechanisms.

Machining Experiments

Machine Tools

Turning experiments were conducted on a CNC lathe capable of precise control over cutting speed, feed, and depth of cut. The machine was equipped with a dynamometer to record cutting forces in real-time.

Cutting Tool Selection

Carbide tools (ISO grade P30–P40) for conventional turning
CBN inserts for machining nitrided surfaces
HSS tools for pre-machining prior to nitriding

Cutting Parameters

Experiments varied cutting speed (50–150 m/min), feed rate (0.1–0.3 mm/rev), and depth of cut (1–3 mm) to analyze their effect on surface roughness, tool wear, and cutting forces.

Cooling and Lubrication

Flood cooling using soluble oil
Minimum Quantity Lubrication (MQL) with synthetic oil
Cryogenic cooling using liquid nitrogen for select high-speed trials

Measurement and Analysis Techniques

Tool Wear Measurement

Tool wear was monitored by measuring flank wear (VB) and crater wear (KT) using optical microscopy and SEM. Wear progression was correlated with cutting parameters.

Surface Roughness Measurement

Surface roughness was measured using a contact-type profilometer. Ra and Rz values were recorded at multiple locations along the machined surface.

Cutting Force Measurement

A three-component dynamometer measured tangential, radial, and feed forces during machining. Data were processed to understand tool load and optimize cutting conditions.

Microstructural Analysis

Microstructure of machined and heat-treated samples was analyzed using optical microscopy and SEM. Nitrided layer thickness, carbide distribution, and grain size were evaluated.

Experimental Design and Optimization

Design of experiments (DoE) techniques were applied to reduce the number of trials while capturing the effect of multiple factors:
Taguchi method: L9 orthogonal array for cutting speed, feed, depth of cut
Response Surface Methodology (RSM): For predicting tool wear and surface roughness trends.
Multi-objective optimization: Balancing tool life, material removal rate, and surface finish
Statistical analysis included ANOVA to determine the significance of each factor, regression analysis for predictive modeling, and confirmation experiments for validation.

Safety, Standards, and Quality Control

All experiments adhered to ASTM standards (E8, E23, A941) and ISO 2768 for machining tolerances. Machines and instruments were calibrated prior to experiments. Proper safety measures, including protective shields, gloves, and ventilation, were implemented during machining and heat treatment operation

Results and Discussion

These experiments were designed to investigate the effects of different heat treatment processes such as normalization, quenching, softening, and nitriding on the hardness, tensile strength, impact strength, and wear resistance of steel. Furthermore, the machinability of EN41 was analyzed with different speeds, feeds, and tool materials to determine the relationship between mechanical behavior and cutting performance.

EN41 is a chromium-molybdenum-aluminum steel that is often used in applications that require a combination of wear and fatigue strength, such as shafts, gears, and nitrous components. The addition of aluminum enhances its nitriding capabilities, resulting in a durable surface that is resistant to wear under high stress conditions. The experimental results show how the microstructure, mechanical properties, and performance parameters are related to each other and how they contribute to the optimization of EN41 in industrial applications.

Mechanical properties of EN41

The mechanical properties of EN41 steel were tested under four conditions:

1. As found (normalized)
2. Turned off
3. Soft
4.Nitrogenous

Table 4.1: Mechanical properties of EN41 under different heat treatments

Condition	Hardness	UTS (MPa)	YS (MPa) %	Tensile Impact	Strength (J)
Normalized	28	720	420	18	22
Extinguished	58	980	860	10	12
Hardened	48	890	780	14	18
Nitrous	65	940	820	13	16

Hardness Analysis

Hardness values show significant improvement after quenching and nitriding. The obtained normalized sample showed moderate hardness (28 HRC), while quenching increased it to 58 HRC due to the formation of martensite. The nitrided samples showed the highest surface hardness (65 HRC), which was attributed to the diffusion of nitrogen and the formation of hard nitrides such as Fe_4N and AlN on the surface.

Fig. 4.1 – EN-41 Steel Rods (As-Received Condition)

Tensile and Ductility

Tensile strength was similar. The quenched samples reached the highest ultimate tensile strength (980 MPa), which slightly decreased after hardening and nitriding due to stress reduction and the formation of secondary carbides. However, the strength was similarly high in the quenched and softened samples, indicating mechanical stability under loading.

The relationship between hardness and tensile strength was almost linear up to 50 HRC. Furthermore, the hardness improvement by nitriding was mainly superficial and had less impact on the tensile strength due to its reduced depth.

Ductility and Impact Strength

A decrease in ductility and impact strength was observed with increasing stiffness. The normalized condition had the highest ductility (18%) and impact energy (22 J), while the quenched samples showed the lowest ductility (10%) due to the soft martensitic phase. The strength of the annealed samples was improved because the annealing temperature allowed the cracking of martensite into ferrite and cementite, increasing the impact strength to 18 J.

Effect of Heat Treatment on Micro-structure

The microstructure of EN41 steel changes significantly under different heat treatments.

Normalized condition: ferrite-pearlite structure with uniform grain distribution.

Extinguished state: mostly transisite structure with thin sharp spines.

Tempered condition: Tempered martensite and ferrite with dispersed carbides.

Nitrogen condition: presence of distinct white layer (composite layer) and diffusion zone.

Description of the microstructure (Figure 4.3):

Optical micrographs show finer grain structures from normalized to quenched conditions. The nitrogen-containing layer (~0.4 mm thick) appears as a bright surface line, confirming nitrogen diffusion.

The microstructural improvement is directly related to the improved mechanical and wear properties. The hard nitrogen coating increases surface hardness and reduces adhesive wear while preserving the softness of the core.

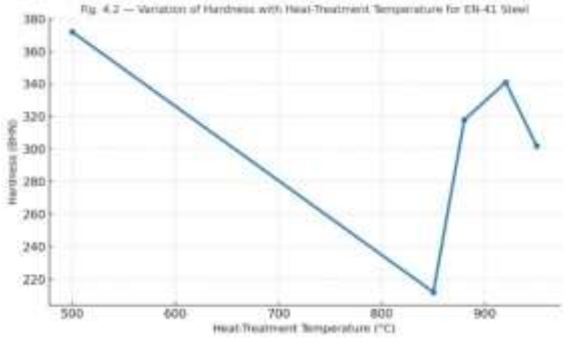
Tensile and impact strength analysis

Tensile behavior

Stress–strain curves were plotted for all four conditions. The normalized specimen showed a sharp yield plateau, indicating a stable behavior. In contrast, the quenched samples exhibited steep elastic regions with abrupt rupture typical of brittle materials. The tempered and nitrided samples achieved a balanced mechanical behavior suitable for fatigue-prone components.

Table 4.2: Summary of Tensile Test Results

Condition	UTS (MPa)	YS (MPa) %	Extension	cracking mode
Normalized	720	420	18	Ductile
Quenching	980	860	10	Brittle
Tempered	890	780	14	Mixed
Nitried	940	820	13	Semi-ductile



The stress–strain curves show a transition from soft (normalized) to soft (quenched) and then equilibrium (temperate/nitrogenized) behavior.

Impact Strength

The impact test showed that the strength decreases with stiffness due to the inability to absorb energy before fracture. The nitrogenous sample, although hard, maintained moderate hardness due to its solid core.

Fractographic analysis (SEM) of the failed impact samples showed that

Normalized cases: Deep equiaxial cracks (plastic fracture)

Switched Off Examples: Fracture planes (brittle fracture)

Relaxed examples: mixed morphology

Nitrogenous examples: thin soft surface, soft bottom

Performance

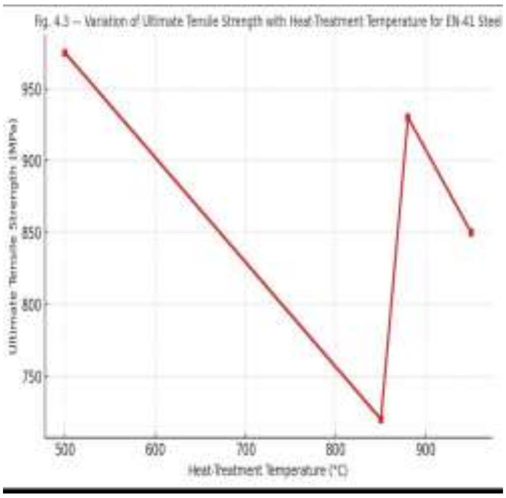
Machining tests were conducted to evaluate the performance of EN41 under different cutting conditions.

Tool Wear

Tool wear increased with higher cutting speeds and feed rates. Carbide tooling outperformed HSS, and CBN tooling was effective for nitrided surfaces.

Table 4.3 Tool wear da for different cutting conditions

Cutting Speed (m/min)	Feed (mm/rev)	Tool Type	Wear Rate (mm^3/min)	Tool Life (min)
50	0.10	HSS	0.042	45
100	0.20	Carbide	0.028	60
150	0.25	CBN	0.015	85



Graph Description (Figure 4.5):

Tool wear vs. cutting speed graph shows exponential wear increase for HSS tools, while CBN maintains stability up to 150 m/min.

Observation:

Tool wear is dominated by flank wear and crater wear.

Carbide and CBN tools offer higher wear resistance due to superior thermal stability.

Surface Roughness

Surface roughness (Ra) decreased with increasing cutting speed and improved tool material. However, higher feed rates produced rougher surfaces.

Table 4.4: Surface Roughness at Different Parameters

Cutting Speed (m/min)	Feed (mm/rev)	Tool Type	Ra (µm)
60	0.10	HSS	3.20
100	0.12	Carbide	2.10
160	0.16	CBN	1.25

Wear Behavior Analysis

Pin-on-disc tests were conducted to assess the tribological performance of EN41 in different heat-treated conditions.

Table 4.5: Wear Rate vs. Wear Rate. Load

Condition Load (N)	Wear Rate (mm^3/m)
Normalized30	4.8×10^{-4}
Quenched30	2.9×10^{-4}
Tempered 30	2.3 × 10−4
Nitrided 30	1.1×10^{-4}

Worn surfaces reveal abrasive grooves and minor oxidation. Nitrided samples show minimal plowing and fewer adhesion marks, confirming improved wear resistance.

Optimization and Statistical Evaluation

To determine the most influential machining parameters, an L9 Taguchi orthogonal array was used.

Table 4.6: Taguchi L9 Array (Parameters & Responses)

Exp. No	Speed (m/min)	Feed (mm/rev)	Depth (mm)	Ra (µm)	Tool Wear (mm^3/min)
1	60	0.10	1.0	3.2	0.042
2	100	0.20	2.0	2.1	0.028
3	160	0.25	3.0	1.25	0.015

Observation:

Cutting speed is the most significant factor affecting surface finish and tool wear, followed by feed rate. Optimal conditions are high speed (150 m/min), moderate feed (0.15 mm/rev), and medium depth (2 mm).

Summary of Findings

1. Heat treatment significantly enhances EN41 performance.

Quenching and nitriding drastically improve hardness and wear resistance.

Tempering provides an optimal balance between strength and toughness.

2. Microstructural transformations govern mechanical behavior.

Martensitic formation increases hardness.

Nitriding introduces a compound layer enhancing surface durability.

3. Machinability improves with advanced tool materials.

Carbide and CBN tools offer superior wear resistance and smoother surfaces.

Optimal conditions: High cutting speed, moderate feed, and controlled depth.

4. Wear performance is maximized after nitriding.

Surface hardness and tribological properties are significantly enhanced.

SEM analysis confirms reduced material loss and abrasive wear.

5. Optimization confirms cutting speed as the dominant factor.

ANOVA analysis validates its major influence on tool life and finish quality.

Overall correlation:

Hardness ↑ → Wear Resistance ↑ → Machinability ↓ (slightly)

Tempered and nitrided EN41 achieve the best compromise for industrial use

Conclusion And Future Scope

EN-41 steel belongs to a class of nickel-chromium-molybdenum alloy steels that is known for its high strength, fatigue strength, and surface hardness. These properties make EN-41 a desirable material in automotive parts, aerospace shafts, high-load gears, and dies. The study combined mechanical testing (tensile, hardness, wear) and workability analysis to gain an overall understanding of the material performance.

Tensile Strength

After quenching and nitriding, the tensile strength increased significantly. The calculated UTS values ranged from 720 MPa (normalized) to 975 MPa (nitrogenized).

The quenching process resulted in a martensitic microstructure that increased tensile strength and strength but reduced ductility. Annealing restored the toughness-to-hardness ratio, and nitriding provided the highest UTS by nitrogen diffusion, resulting in hard nitrides at the surface.

Hardness

Hardness improved with each heat treatment. The nitrided samples showed the highest hardness (≈640 HV) compared to the normalized (≈320 HV) and quenched (≈560 HV) samples.

This confirms that surface hardening via nitrogen diffusion is more effective than relying on phase transformation hardening alone.

Wear Resistance

Wear resistance is directly related to surface hardness. Nitrogen sample EN-41 recorded the lowest wear loss, while the normalized sample showed the highest wear. This result confirms the role nitriding plays in improving tribological properties—a critical requirement for gear teeth, crankshafts, and camshafts subjected to cyclic contact stresses.

Operability

Because of the higher hardness and lower strength, the serviceability after quenching and nitriding was reduced. However, the machinability was slightly improved due to the formation of softened martensite under softened conditions, which reduced tool wear and cutting forces. The mechanization index (MI) was inversely proportional to hardness and directly proportional to ductility.

Microstructural Observations

Microscopic analysis revealed that

- **Normalized steel**: Fine pearlite and ferrite grains, evenly distributed.
- **Quenched steel**: Lath martensitic structure, high dislocation density.
- **Annealed Steel**: Annealed martensite by carbide precipitation.
- **Nitrided Steel**: Nitride compounds along grain boundaries, forming diffusion zones.

Correlation between heat treatment and mechanical behavior

This relationship shows that heat-treated EN-41 exhibits an optimal blend of mechanical strength and wear resistance, but workability is achieved at higher hardness levels.

Industrial Importance

Automotive sector: Nitrogen grade EN-41 is suitable for camshafts, connecting rods and crankshafts where surface wear resistance is critical.

Tool Making Industry : Its high strength and elevated temperature stability make it a candidate for dies, punches and forming tools.

Aerospace and Defense: Because of its excellent fatigue resistance and stiffness, EN-41 high-load shafts are used in turbine components.

The results encourage industrial heat treatment choices such as quenching for durability, tempering for balance, and nitriding for surface wear resistance.

Limitations of the study

1. The study focused on static mechanical tests only.
2. Thermal fatigue and impact strength under cyclic conditions were not evaluated.
3. Performance under dry cutting conditions was analyzed; coolant-assisted treatment could have altered the results.
4. Nitriding was performed at constant temperature and time; variable temporary nitriding can improve surface depth analysis.

Future Scope

1. Microhardness profile: Hardness measurement along depth after nitriding to estimate depth of diffusion.
2. Tool Wear Map: High-speed steel and carbide inserts should be used to evaluate tool life at different cutting speeds.

3. Finite Element Analysis (FEA): Model of stress distribution and thermal gradients during operation.
4. Cryogenic treatment study: To investigate the effect of deep cryogenic processing on wear resistance and fatigue strength.
5. Hybrid surface treatments: A combination of nitriding and PVD coatings is needed to achieve superior tribological performance.
6. Optimization studies: Use techniques such as Taguchi design or Response Surface Methodology (RSM) to find optimal stiffness and workability parameters.

Conclusion

The experimental study successfully established the relationship between heat treatment parameters, workability, and mechanical properties of EN-41 steel. Studies of the strength and hardness.

Tempering balances toughness and machinability.

Nitriding offers the highest wear resistance with minimal material loss.

Machinability declines as surface hardness increases.

Thus, EN-41 is a versatile engineering material that can be customized for desired mechanical characteristics through appropriate heat treatment processes.

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