Comparative Evaluation of Heat Treated Steel Alloys for Reduction Gearbox Components

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Abstract

Traditionally, leading global manufacturers have used Chromium Molybdenum Steel 415 (SCM415) to manufacture gears due to its exceptional hardenability and superior mechanical properties after carburizing. However, the limited availability of Chromium Molybdenum Steel415 in India has led to the exploration of alternative materials to fulfill the demand for reduction gearbox components. In India, Emergency Number-19 (EN-19), Carbon 45 (C-45), and Stainless Steel 410 (SS410) are common alternative materials that provide comparable mechanical properties. These materials are readily available in the Indian market, making them viable options for manufacturers facing shortages of SCM415. In order to complete the work, various tests like Tensile test, Hardness test and Microstructure test are being done on the above materials before and after two different heat treatment process. It has been found out that materials EN 19, C45, and SS 410 exhibit distinct mechanical properties and microstructural characteristics, offering potential alternatives to SCM 415. After the induction hardening process, C45 shows a hardness of 61 HRC which is much higher than EN-19 and SS410.

Keywords: Chromium Molybdenum Steel 415 (SCM415), Emergency Number-19 (EN-19), Carbon 45 (C-45), Stainless Steel 410 (SS410), Alternative Materials, Tensile Test, Hardness Test, Microstructure Test, Microstructural Characteristics, Carburizing, Induction Hardening, Hardenability.

1. Introduction

Reduction gearboxes are essential components in industrial machinery, regulating rotational speed and torque to optimize performance. They utilize various gears—including spur, helical, bevel, and planetary—selected based on specific operational needs. These gearboxes vary in design to accommodate gear ratio, input/output speeds, torque capacity, and spatial constraints, with ongoing advancements improving efficiency, reliability, and durability. Research focuses on optimizing gear design, lubrication, noise reduction, vibration control, and fault diagnosis.

Key materials used in these gearboxes include SCM415 for its hardenability and strength, EN-19 for toughness and fatigue resistance, C45 for machinability and wear resistance, and SS410 for moderate corrosion resistance and high strength. Carburizing and induction hardening are crucial heat treatment processes that enhance surface properties such as hardness, wear resistance, and durability. Given the limited availability of SCM415 in India, primarily imported from Japan, alternatives like EN-19, C45, and SS410, which are locally accessible, are being evaluated as substitutes.

This study assesses EN-19, C45, and SS410 through composition analysis, tensile testing, hardness testing, and microscopic examination to determine their suitability as substitutes for SCM415. It explores the effects of carburizing and induction hardening on these materials to enhance their performance characteristics. By systematically comparing these alternatives, the research aims to provide cost-effective and high-performance solutions to overcome the challenges posed by the limited availability of SCM415 in the Indian manufacturing sector.

Objective

The objective of this study is to evaluate the suitability of EN-19, C45, and SS410 as alternative materials for reduction gearbox gears, intended to replace SCM415. This evaluation involves analyzing the chemical composition, mechanical properties, and microstructure of these materials before and after carburizing heat treatment.

2. Literature Survey

The literature survey explores the current state of materials used in gear manufacturing, focusing on the performance and availability of different alloys in India. It reviews studies on EN-19, C45, and SS410, highlighting their mechanical properties, hardening capabilities, and suitability for high-stress applications. Comparative analyses with SCM415, a commonly used gear material, are discussed to establish benchmarks for performance and cost-effectiveness. This also, evaluates the necessity of comprehensive testing to identify viable alternatives to SCM415, particularly in the context of the Indian manufacturing industry.

In their 2018 study, Das and Das investigated how varying the gas carburizing process parameters (temperature, time, and gas composition) affects the hardness of AISI 4140 steel, finding that precise control of these parameters optimizes hardness and enhances the steel's performance and durability, providing valuable guidelines for the metallurgical industry [1]. In their 2015 study, Kumar and Tewari reviewed how carburizing process parameters (temperature, time, and gas composition) affect the surface hardness of low carbon steel, finding that optimizing these parameters significantly enhances hardness and durability, offering valuable insights for improving carburizing processes in the metallurgical industry [2]. In their 2017 study, Singh and Khanduja investigated how carbonitriding affects the microstructure and mechanical properties of low carbon steel, finding that the treatment significantly enhances hardness, wear resistance, tensile strength, and toughness, making the steel suitable for diverse industrial applications [3].In their 2019 study, Gupta and Prakash investigated the availability and utilization of materials in the Indian manufacturing sector, finding significant variability among industries and highlighting opportunities to improve resource management practices for enhanced efficiency and sustainability [4]. In their 2018 study, Rajan, Sharma, and Sharma investigated the effects of various heating and quenching methods on EN-19 steel, finding that these processes significantly impact its hardness and toughness, underscoring the importance of optimized heat treatment for enhancing mechanical strength and structural integrity in industrial applications [5].

In 2017, Kapoor studied the effects of carburizing on the microstructure and mechanical properties of EN-19 steel, demonstrating that carburizing significantly increased surface hardness, wear resistance, and overall mechanical strength, making the steel suitable for high-stress industrial applications like gears and shafts [6].In 2020, Das and Bhattacharya conducted a comparative study on the microstructure and mechanical properties of C45 steel and SS410 steel, revealing notable differences in grain size, phase distribution, hardness, tensile strength, and impact resistance, providing valuable insights for selecting appropriate materials in engineering applications [7]. Avner's 2011 book "Introduction to Physical Metallurgy" introduces principles essential to understanding metallurgical science, covering topics like crystal structure, phase diagrams, mechanical properties of metals, and metallurgical processes, and emphasizing the relationship between microstructure and mechanical properties, demonstrating the role of physical metallurgy in material design, process optimization, and enhancing industrial performance [8]. Totten's (2007) book "Steel Heat Treatment: Equipment and Process Design" provides essential guidance on optimizing heat treatment processes in steel manufacturing, emphasizing precise heating and cooling control to enhance efficiency, reliability, and quality, crucial for improving steel performance [9]. Kumar and Jha's (2020) work "Heat Treatment and Surface Engineering of Steels" offers an overview of heat treatment techniques and surface engineering methods in metallurgy, highlighting how these processes enhance mechanical properties, wear resistance, surface hardness, and corrosion resistance of steel components, serving as a valuable resource for optimizing steel performance and durability [10].

Callister Jr. and Rethwisch's (2010) textbook "Materials Science and Engineering: An Introduction (8th ed.)" provides foundational knowledge in materials science and engineering, integrating theory with practical insights on crystal structures, phase transformations, mechanical properties, materials selection, processing methods, and property optimization, essential for addressing real-world engineering challenges across diverse applications [11]. Dieter and Bacon's (2008) "Mechanical Metallurgy" focuses on the mechanical behavior of metals, covering topics like dislocation theory, strengthening mechanisms, and fracture mechanics, influencing materials science and metallurgical engineering for optimizing material performance and reliability in industrial settings [12]. Groover's (2019) "Fundamentals of Modern Manufacturing: Materials, Processes, and Systems (6th ed.)" integrates theoretical foundations with practical applications in modern industrial production, emphasizing material properties, manufacturing processes, advanced technologies, sustainability, and automation to enhance productivity and quality [13]. Bhadeshia's (2016) "Steels: Microstructure and Properties (4th ed.)" explores metallurgical characteristics, alloying effects, and heat treatment impacts on steel microstructures, guiding advancements in steel metallurgy for high-performance applications [14]. Davis's (2001) "Surface Hardening of Steels: Understanding the Basics" covers surface hardening techniques like Carburizing, Nitriding, Induction hardening, and Flame hardening, offering insights into enhancing steel properties for engineers and researchers in materials processing and surface engineering [15].

Reduction Gearboxes

Reduction gearboxes are indispensable components within industrial machinery, facilitating the regulation of rotational speed and torque to optimize operational performance [16]. They serve a crucial function in tasks necessitating precise power transmission manipulation, enabling adjustments to rotational speeds as per specific operational needs [17]. Within these gearboxes, a variety of gear types such as spur gears, helical gears, bevel gears, and planetary gears are employed to achieve the desired speed reduction and torque amplification [18]. Each gear type offers distinct advantages, selected based on the application's requirements and performance criteria [19].

Heat Treatment Processes

The decision to perform heat treatment, including carburizing, was influenced by the gear manufacturing practices of leading companies like Nabtesco, which utilize SCM415 material carburized up to 58-62 HRC for their RV-N series input gears. Therefore, to evaluate alternative materials such as SAE4140, C45, and SS410, it was essential to subject them to similar heat treatment processes to assess their mechanical and chemical properties under comparable conditions. This approach allows for a comprehensive comparison to determine if the alternative materials meet the required performance standards set by industry practices [20].

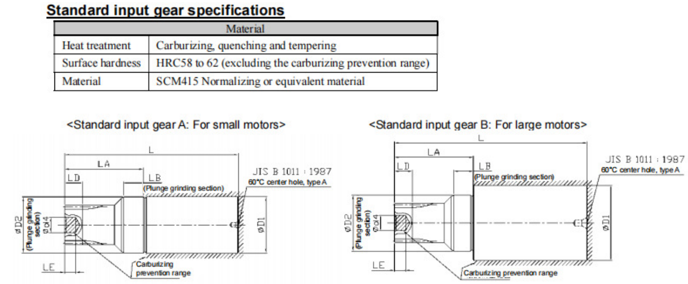


Figure - 2a Material specification and heat treatment values of Nabtesco RV-N series input gear [20]

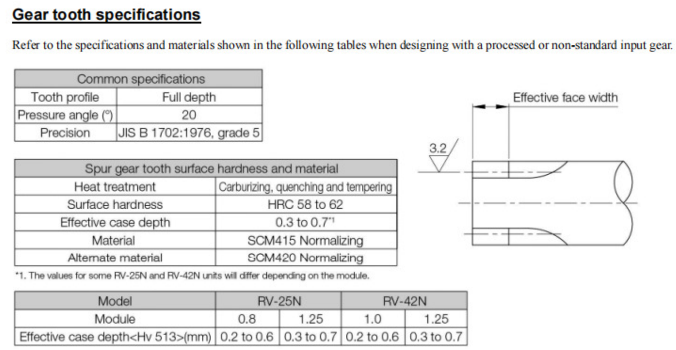
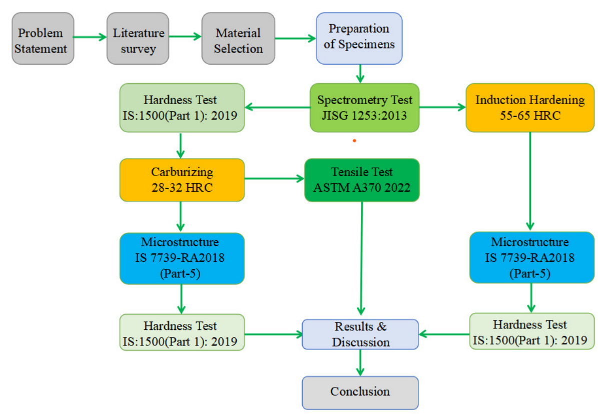


Figure - 2b Material specification and heat treatment values of Nabtesco RV-N series spur gear tooth [20]

Methodology

The following flow chart shows the main testing steps:



The methodology for testing involves the following steps:

1. **Spectrometry Test:** This test is to confirm the chemical composition of Specimens using spectrometry analysis.
2. **Brinell Hardness Test:** This test aims to evaluate the hardness value of specimens before heat treatments process.
3. **Heat Treatment-1 for Specimens 1 & 2** : Heat treatment is applied to Specimens 1 and 2 to achieve a hardness level of 28-32 HRC.
4. **Tensile Test for Specimen 1**: A tensile test is conducted on Specimen 1 after heat treatment 1
5. **Brinell Hardness Test, and Microstructure Test for Specimen** 2: Hardness testing and Microstructural analysis are done on Specimen 2 after heat treatment-1

6. **Heat Treatment-2 for Specimen 3** : Specimen 3 undergoes a heat treatment process to achieve a higher hardness level of 55-65 HRC, similar to the hardness range typically found in reduction gearbox components.

7. **Brinell Hardness Test, and Microstructure Test for Specimen 3**: Hardness testing and Microstructural analysis are done on Specimen 3 after heat treatment-2

3. Experimental work

This section explains the selection of materials that are widely available in India and perform well after hardening. EN-19, C45, and SS410 were chosen for evaluation considering SCM415 as benchmark. Tests conducted include composition analysis, tensile testing, hardness testing, and microscopic examination to determine their suitability as alternatives to SCM415 for gear manufacturing. The experimental procedures for EN-19, C45, and SS410 are detailed here.

Materials Selection

EN-19, C45, and SS410 were selected for evaluation due to their availability in India and anticipated performance after different heat treatments. These materials are important for industries requiring robust mechanical properties and enhanced durability in high-stress applications. Their suitability aligns with ongoing research efforts aimed at optimizing material selection and heat treatment methods for improved performance and cost-effectiveness in manufacturing processes [29].

Figure - 3a Raw materials procured

Raw materials procured were 32 mm diameter and 300 mm length. They were then machined to following sizes.

Sample 1: Diameter of 30 mm and length of 250 mm

Sample 2: Diameter of 30 mm and length of 50 mm

Sample 3: Diameter of 30 mm and length of 50 mm

4. Results & Discussion

Following are the results obtained after conducting various Heat treatment processes and Mechanical tests.

4.1 Optical Emission Spectrometry

After conducting the Optical Emission Spectrometry (OES) test as per JISG 1253:2013 standard, following result were found out.

Table 4.1 - Optical Emission Spectrometry test result

Element	EN-19	C-45	SS410
C	0.42%	0.43%	0.12%
Ni	0.28%	0.25%	0.40%
Mn	0.76%	0.74%	0.86%
P	0.027%	0.015%	0.017%
S	0.013%	0.002%	0.014%
Cr	1.01%	-	12.29%
Mo	0.16%	-	-

4.2 Brinell Hardness Test - 1

Following results were obtained after conducting Brinell hardness test.

Figure - 4.2 Raw materials procured

Method : As per IS-1500(Part-1):2019

Load : 187.5 Kg

Indenter Dia : 2.5 mm

Indenter : Tungsten Ball

Table 4.2 - Brinell Hardness test result

Hardness Test 1 - Specimen - 1						
SL. No.	Material	Reading in HBW for Specimens			Average Results in HBW	Average Results in HRC
		Position 1	Position 2	Position 3		
1	EN-19	321	321	321	321	34
2	C45	174	174	174	174	6
3	SS410	156	156	156	156	3

4.3 Heat treatment - 1 (Carburizing)

Gas carburizing is the heat treatment process applied to EN-19, C45, and SS410 steels, following the standards outlined in IS13417:1992. Each sample, sized at 30 mm in diameter and 50 mm in length, underwent carburizing at temperatures ranging from 900°C to 950°C for a duration of 5 hours. This process aimed to achieve a case depth of approximately 1 mm, enhancing surface hardness within the expected range of 28-32 HRC.

After carburizing, the components were quenched in oil to rapidly cool and harden the surface layer, followed by tempering between 150°C to 200°C for 1 to 2 hours. Tempering allowed for the reduction of internal stresses and adjustment of hardness, ensuring the final mechanical properties met specific application requirements.

Standard	:	IS13417:1992
Sample size	:	30 dia x 50 length
Expected hardness range	:	28-32 HRC
Carburizing temperature	:	900°C to 950°C
Carburizing duration	:	5 hours
Case depth	:	1 mm
Quenching medium	:	Oil
Tempering temperature	:	150°C to 200°C
Tempering Duration	:	1 to 2 hours

Figure - 4.3 - Samples after carburizing

4.4 Tensile Test

Following Tensile test were conducted as per ASTM A370 2022 standard and following results were obtained after heat treatment of specimens to 28-32 HRC.

4.4.1 Tensile test on SS410

Gauge Length (mm)	:	50
Gauge Diameter (mm)	:	12.45
Final Gauge Length (mm)	:	68.33
Initial Area (mm2)	:	12.74
Final Cross section Area (mm2)	:	35.47
Max. Load (KN)	:	63.752
Displacement at Max. Load (mm)	:	20.72
Max. Displacement (mm)	:	30.25
Yield Load (KN)		: 36.576
Ultimate Tensile strength/Yield strength		: 1.743
Ultimate Stress (MPa)		: 524
Yield Stress (MPa)		: 300
Elongation (in %)		: 36.66
Reduction in Area (in %)		: 70.864

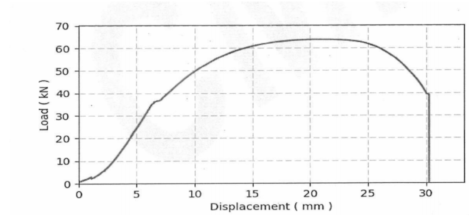


Figure - 4.4.1a - Load vs Displacement graph of SS410 during Tensile test

Figure - 4.4.1b - SS410 after Tensile test

Figure - 4.4.1c - The fracture surface of SS410 after Tensile test

The rough and fibrous fracture surface shows that the material has stretched a lot before breaking. This shows that material is highly ductile.

4.4.2 Tensile test on EN-19

Gauge Length (mm)	:	50
Gauge Diameter (mm)	:	12.5
Final Gauge Length (mm)	:	57.6
Initial Area (mm2)	:	122.72
Final Cross section Area (mm2)	:	80.6
Max. Load (KN)	:	119.896
Displacement at Max. Load (mm)	:	16.61
Max. Displacement (mm)	:	20.42
Yield Load (KN)	:	106.04
Ultimate Tensile strength/Yield strength		: 1.131
Ultimate Stress (MPa)		: 977
Yield Stress (MPa)		: 864
Elongation (in %)		: 15.2
Reduction in Area (in %)		: 34.322

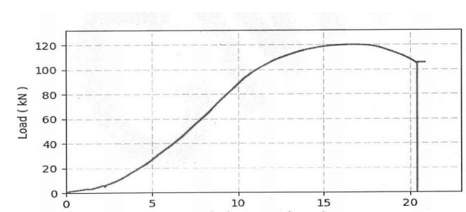


Figure - 4.4.2a - Load vs Displacement graph of EN-19 during Tensile test

Figure - 4.4.2b - EN-19 after Tensile test

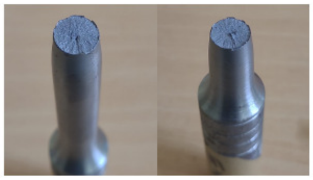


Figure - 4.4.2c - The fracture surface of EN-19 after Tensile test

The fracture surface shows minimal visible deformation, appearing smooth and flat, indicating little to no plastic deformation and characterizing the material as brittle.

4.4.3 Tensile test on C-45

Gauge Length (mm)	:	50
Gauge Diameter (mm)	:	12.51
Final Gauge Length (mm)	:	65.2
Initial Area (mm2)	:	122.91
Final Cross section Area (mm2)	:	58.77
Max. Load (KN)	:	73.264
Displacement at Max. Load (mm)	:	20.14
Max. Displacement (mm)	:	27.24
Yield Load (KN)	:	46.888
Ultimate Tensile strength/Yield strength	:	1.563
Ultimate Stress (MPa)	:	596
Yield Stress (MPa)	:	381
Elongation (in %)	:	30.4
Reduction in Area (in %)	:	52.185

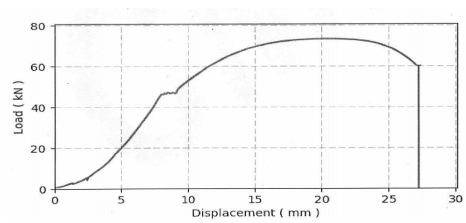


Figure - 4.4.3a - Load vs Displacement graph of C-45 during Tensile test

Figure - 4.4.3b - C-45 after Tensile test

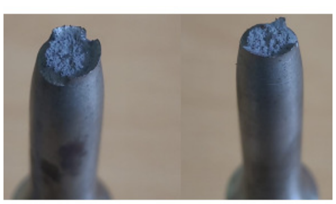


Figure - 4.4.3c - The fracture surface of C-45 after Tensile test

The rough and fibrous fracture surface shows that the material has stretched a lot before breaking. This shows that material is highly ductile.

4.5 Heat treatment - 2 (Induction Hardening)

Induction hardening processes were applied to EN-19, C45, and SS410 steels following the IS13417:1992 standard, using samples sized at 30 mm in diameter and 50 mm in length to achieve a uniform case depth of approximately 1 mm across all materials.

Table 4.5 - Heat treatment parameters for EN-19, C-45 and SS410

Material	EN-19	C45	SS410
Induction Hardening Temperature (°C)	350 - 400	600 - 800	350 - 400
Induction Hardening Duration	10 - 20 seconds	15 - 30 seconds	10 - 20 seconds
Quenching Medium	Distilled water & 4% polymer oil		
Tempering Temperature (°C)	150 - 250	150 - 250	200 - 300
Tempering Duration	1 - 2 hours	1 - 2 hours	1 - 2 hours
Expected Hardness Range (HRC)	40 - 45	55 - 65	40 - 45

Figure - 4.5 - Samples after induction hardening

4.6 Microstructure Test- 1 & Hardness Test- 2

Following Microstructure analysis test were conducted on all samples as per "IS 7739-RA2018 (Part-5), ASM hand book vol 7th & 9th edition" standard and following results were obtained after heat treatment of specimens to 28-32 HRC.

● **Material**	**:**	**C45**
Magnification	:	1000X
Microstructure	:	Structure consists of spheriodized cementite and lamellar pearlite & ferrite
Hardness range	:	28 to 32 HRC
Observed value	:	28, 28, 29 HRC

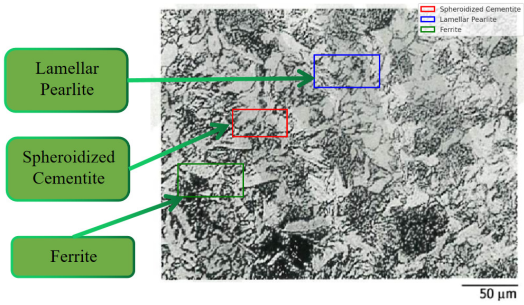


Figure - 4.6a - Microstructure Image (1000x) of C-45 specimen after heat treatment-1

Observations:

- **Spheroidized Cementite:** This phase indicates that the carbon present in the steel has transformed into rounded, globular particles, enhancing toughness and machinability.
- **Lamellar Pearlite:** Comprised of alternating layers of ferrite and cementite, this phase provides a balance of strength and ductility.
- **Ferrite**: This softer phase contributes to the overall ductility of the steel, ensuring that the material can undergo deformation without cracking.

Surface Hardness Analysis: The expected surface hardness range for C45 is 28 to 32 HRC. Observed values from hardness testing fall within this range, measuring at 28, 28, and 29 HRC. This consistency indicates successful heat treatment and achievement of the desired mechanical properties.

The microstructure analysis shows that C45 steel has a mix of spheroidized cementite, lamellar pearlite, and ferrite. The observed surface hardness values match the expected range, confirming the material has the right mechanical properties. This makes C45 ideal for tough applications in automotive parts, machinery components like gears and shafts, and structural elements that need strength, toughness, and ease of machining.

- **Material : EN-19**

Magnification : 500X

Microstructure : Structure consists of Tempered martensite

Hardness range : 28 to 32 HRC

Observed value : 32, 32, 31 HRC

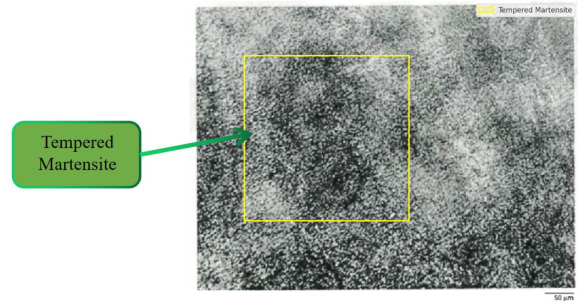


Figure - 4.6b - Microstructure Image (500x) of EN-19 specimen after heat treatment-1

Observations:

- **Tempered Martensite:** The microstructure is characterized by tempered martensite, a hardened structure formed during the tempering process. This phase provides EN-19 with a desirable balance of strength, toughness, and ductility, making it suitable for various mechanical applications.
- **Surface Hardness Analysis:** The expected surface hardness range for EN-19 is 28 to 32 HRC. The observed values obtained from hardness testing closely align with the specified range, measuring at 32, 32, and 31 HRC. This indicates that the material has achieved the desired level of hardness.

Microstructure analysis shows that EN-19 has evenly distributed tempered martensite, which gives it strong mechanical properties. The observed surface hardness values confirm it's suitable for tough jobs like gears and shafts in heavy-duty components in automotive and machinery industries.

- **Material : SS410**

Magnification : 1000X

Microstructure : Banded delta ferrite in a matrix of martensite

Hardness range : 28 to 32 HRC

Observed value : 29, 28, 30 HRC

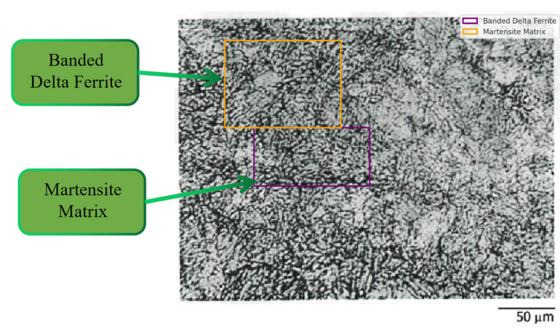


Figure - 4.6c Microstructure Image (1000x) of SS-410 specimen after heat treatment-1

Observations:

- **Banded Delta Ferrite:** The presence of banded delta ferrite is evident from the alternating bands visible in the microstructure image. These bands indicate variations in chemical composition and cooling rates during the material's processing.

- **Martensitic Matrix:** The dominant phase of martensite imparts SS 410 with its characteristic hardness and strength, contributing to its suitability for various applications requiring high mechanical performance.

Surface Hardness Analysis: The expected surface hardness range for SS 410 is 28 to 32 HRC. Observed values obtained from hardness testing align closely with the specified range, measuring at 29, 28, and 30 HRC. This indicates that the material has achieved the desired level of hardness.

The microstructure analysis shows that SS 410 has a balanced composition that contributes to its hardness and strength.

4.7 Microstructure Test- 2 & Hardness Test- 3

Following Microstructure analysis test results were obtained after heat treatment of specimens to 55-65 HRC.

• **Material**	**:**	**C-45**
Magnification	:	1000X
Microstructure	:	Structure consists of fine tempered martensite and retained austenite
Hardness range	:	58 to 62 HRC
Observed value	:	61, 61, 62 HRC

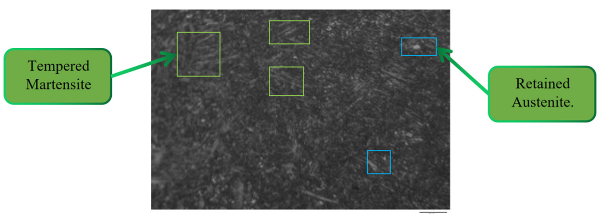


Figure - 4.7a - Microstructure Image (1000x) of C-45 specimen after heat treatment-2

Observations:

Fine Tempered Martensite: This phase, resulting from the tempering process, provides the steel with a high level of hardness and strength while maintaining some degree of toughness.

Retained Austenite: The presence of retained austenite contributes to the material's overall stability and can affect hardness and mechanical properties, providing a balance between hardness and toughness.

Surface Hardness Analysis: The expected surface hardness range for C45 is 58 to 62 HRC. Observed values from hardness testing are within this range, measuring at 61, 61, and 62 HRC. These values indicate that the material has achieved the desired level of hardness, essential for its intended applications.

The microstructure analysis shows that C45 steel has both fine tempered martensite and retained austenite, giving it high hardness and strength. The observed surface hardness values match the expected range, confirming effective heat treatment. These qualities make C45 ideal for tough jobs needing wear resistance and durability, like gears, cutting tools, dies, and heavy-duty machinery parts.

• **Material**	**:**	**EN-19**
Magnification	:	500X
Microstructure	:	Spheriodized pearlite with ferrite matrix
Hardness range	:	40 to 45
Observed value	:	36, 37, 39

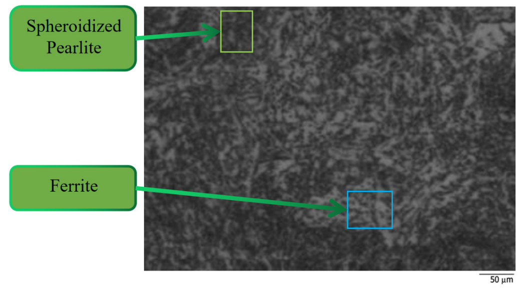


Figure - 4.7b- Microstructure Image (500x) of EN-19 specimen after heat treatment-2

Observations:

- **Spheroidized Pearlite:** This phase indicates that the cementite within the pearlite has transformed into spherical particles, enhancing the material's toughness and machinability.
- **Ferrite Matrix:** The soft ferrite phase provides ductility and contributes to the overall malleability of the steel.

Surface Hardness Analysis: The expected hardness range for EN-19 is 50 to 52 HRC. Observed values from hardness testing are significantly lower, measuring at 36, 37, and 39 HRC. These values indicate that the material has not achieved the desired hardness level.

The microstructure analysis of EN-19 shows spheroidized pearlite in a ferrite matrix, which is good for toughness and machining. However, the hardness values observed are lower than expected, indicating that the heat treatment process didn't reach the desired hardness. This suggests there may be a problem with how the steel was heated and cooled, which needs to be fixed to meet the required standards. The current hardness may not be enough for tough jobs, so more research is needed to make EN-19 steel stronger.

Material	**:**	**SS410**
Sample size	:	30mm dia x 100mm length

Magnification	:	1000X
Microstructure	:	Structure consists of Banded delta ferrite in a matrix of martensite
Hardness range	:	40 to 45 HRC
Observed value	:	39, 40, 40 HRC

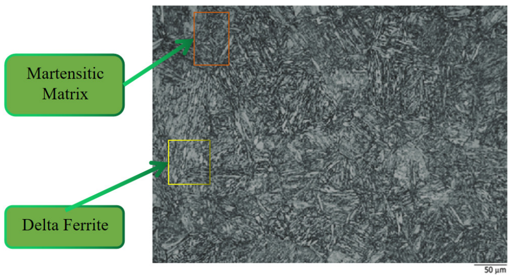


Figure - 4.7c - Microstructure Image (1000x) of SS-410 specimen after heat treatment-2

Observations:

- **Banded Delta Ferrite:** The presence of banded delta ferrite indicates the formation of alternating bands of ferrite within the steel, which can affect the material's mechanical properties and corrosion resistance.
- **Martensitic Matrix:** The martensitic structure imparts SS 410 with high hardness and strength, crucial for various industrial applications.

Surface Hardness Analysis: The expected hardness range for SS 410 is 40 to 45 HRC. Observed values from hardness testing are 39, 40, and 40 HRC. These values are slightly below the lower limit of the specified range but very close, indicating near achievement of the desired hardness.

The microstructure analysis of SS 410 shows a mix of banded delta ferrite and a martensitic structure, which affects its mechanical properties. The observed hardness values are slightly lower than expected, indicating the material is nearly at the desired hardness but not quite there. This small difference may not affect performance much, but adjusting the heat treatment process could help achieve the exact hardness needed.

4.8 Mechanical Properties Comparison

Following is the Mechanical Properties Comparison after Tensile Test & Hardness Test for all materials before heat treatment and after carburizing and induction hardening.

Table - 4.8 - Mechanical Properties Comparison

Material	Mechanical Properties	Before Heat Treatment	After Carburizing	After Induction Hardening
SCM415	UTS (MPa)	655	700 - 900	1200 - 1500
	YS (MPa)	~415	470 - 620	1000 - 1300
	Elongation	12 - 17%	15 - 25%	<10%
	Hardness (HRC)	5 - 15	28 - 32	58 - 62
EN-19	UTS (MPa)	655	977	1236
	YS (MPa)	~415	864	-
	Elongation	25.70%	15.20%	-
	Hardness (HRC)	321 HB (34)	32	39
C45	UTS (MPa)	560 - 700	596	-
	YS (MPa)	280 - 430	381	-
	Elongation	14 - 17%	30.40%	-
	Hardness (HRC)	174 HB (6)	28	61
SS410	UTS (MPa)	510	523	1265
	YS (MPa)	290	300	-
	Elongation	34%	36.66%	-
	Hardness (HRC)	156 HB (3)	29	40

UTS of EN-19 and SS410 have been converted with ref. to the hardness value achieved by following IS0 18265:2013 standard [64].

4.9 Microstructural Characteristics Comparison

Following is the Microstructural Characteristics Comparison for all materials after heat treatment 1 & 2 with SCM415.

After the first heat treatment, C45 steel shows a mix of spheroidized cementite, lamellar pearlite, and ferrite, with surface hardness suitable for automotive parts, machinery, and structures due to its strength and machinability. EN-19 exhibits uniform tempered martensite, ideal for strong gears and shafts. SS 410 displays balanced hardness and strength, suitable for tough applications.

After the second heat treatment, C45 steel develops fine tempered martensite and retained austenite, enhancing its hardness and strength for wear-resistant gears and tools. EN-19, however, shows spheroidized pearlite and lower-than-expected hardness, indicating a need for improved heat treatment. SS 410, with banded delta ferrite and martensitic matrix, needs slight adjustments for precise hardness. These results highlight the importance of precise heat treatment for optimizing steel properties.

4.10 Comparing Hardness values with SCM415

SCM 415 has the highest hardness range of 58 - 62 HRC, making it very tough and ideal for tough gear applications that demand exceptional hardness. This extreme hardness is beneficial where durability and resistance to wear are crucial, making SCM 415 a preferred option for such uses.

EN-19, although not detailed in the third set of results, shows a hardness of 39 HRC in the second set. While this is lower than SCM 415, it still signifies a considerable level of hardness, indicating EN-19's ability to handle moderate to high mechanical stress.

C45 and SS410 have hardness levels of 61 HRC and 40 HRC, respectively, offering moderate to high hardness. While both materials provide sufficient hardness for many applications, they may not be as suitable for extremely demanding conditions as SCM 415 or even EN-19.

In summary, SCM 415 stands out for its superior hardness, making it a preferred choice for applications requiring exceptional hardness and wear resistance. Nonetheless, EN-19, C45, and SS410 also exhibit significant hardness levels, presenting viable alternatives depending on specific application needs.

5. Conclusion

Based on this study aiming to find alternatives to SCM 415 for gearbox components in India, EN-19, C45, and SS 410 were tested rigorously. After the first heat treatment, C45 showed a balanced microstructure suitable for automotive and structural uses. EN-19 displayed promising uniform martensitic distribution, while SS 410 showed adequate hardness and strength for tough environments. However, EN-19's second heat treatment revealed spheroidized pearlite needing improvement for high-stress applications, highlighting the need for precise heat treatment. SS 410, although needing minor adjustments, showed potential but slightly lower properties compared to C45 and EN-19. Limitations included not conducting a tensile test to fully compare mechanical properties after the second heat treatment. Improper heat treatment affected EN-19's hardness, which was lower than expected. SS 410 also fell slightly short in hardness due to sub-optimal treatment conditions. Future research should address these limitations by including tensile testing and refining heat treatment methods, especially for EN-19 and SS 410, to ensure consistent performance and meet mechanical specifications for gearbox applications. Despite challenges, EN-19, C45, and SS 410 show promise as viable alternatives in India, pending improvements in heat treatment processes to optimize their performance.

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