ABSTRACT
This paper discusses the effect of surface heat treatments and its parameters on the fatigue property enhancement of steel. The fatigue failure of steel is due to the repeated and alternative loads over them. Due to this frequent loading the life span of materials reduces. Rotary elements undergoing fatigue failure is most common in transmission shafts, crankshafts and gears. By heat treating the metals they are relieved from residual stress, required micro granular structures obtained, surface hardness improves which obviously leads to fatigue life improvement. This study shows the possible ways of fatigue life enhancement through heat treatments and their comparative effects over the mechanical properties of steel. By altering heat treatment parameters, mechanical properties can be altered to increase fatigue life and surface hardness. Ideas of research undertaken over heat treatments that enhance fatigue life are presented in this paper. This study compares the results of various surface heat treatments and their effects, so that a new method of combinational heat treatments can be obtained for a better result.

KEYWORDS: annealing, normalizing, martensite, quenching, tempering, austempering, induction hardenting, nitriding, austenite, carburizing, hardness, micro granular structure and fatigue strength.

INTRODUCTION
Even though the field of Automobile has evolved furthermore, the unavoidable phenomenon of rotating elements subjected to variable loading is Fatigue. Fatigue failure is the important concern in design of engineering components. The most engineering components failing due to fatigue are made of steel and cast iron that undergoes rotational operational like crank shaft, connecting rod, axle, transmission shaft and gear. The Fatigue resistance of a structural component can be influenced through the effects of environmental, mechanical and metallurgical variables [1]. The defects on surface and subsurface of high strength steels reduce the Fatigue limit [2]. The production of crankshaft in Automobile industry is mostly utilizing the EN8 steel for good strength and toughness. Fatigue failure is the major reason to the components undergoing repeated loads [3]. The defect is due to the wide range of variation or fluctuation in the applied stress of high value. At the stress concentration sites the fatigue failure starts by crack initiation and continues through the plane perpendicular to applied load. The crack on reaching the surface grows and breaks down the component. The factors affecting fatigue are material type, surface properties, residual stress, micro granular size, environment condition, and temperature and stress rate. Surface treatments on machine elements can improvise the fatigue behaviors.
Heat Treatment:
A. Carburising:
There are several heat treatments available for enhancing fatigue strength like carburizing, annealing, quenching, hardening, tempering, nitriding and induction hardening. Each treatment has certain effect on fatigue strength enhancement. Heat treatments only vary through heating time, frequency, temperature, cooling rate, diffusion agents and micro granular size, but aimed to improve mechanical properties.

Through low temperature para equilibrium carburization process the crack initiation is shifted from surface to core in the 316l austenitic stainless steel. Through this process at 25 µm case depth, the surface hardness and surface compressive stress more than 2GPa achieved and increases the endurance limit from 200 to 325 MPa [4].

For low carbon steels the carburization performed at various temperatures with various quenching mediums shown in following table 1. It is suggested here for a lower value of activation energy, so that process becomes more effective by utilizing less energy for the carbon atoms to get diffused into carbon steel.

<table>
<thead>
<tr>
<th>Carburizing Temperature</th>
<th>carburizing hour</th>
<th>carbon layer thickness</th>
<th>Quenching Medium</th>
<th>surface hardness values</th>
</tr>
</thead>
<tbody>
<tr>
<td>850°C</td>
<td>8,10,12 hours</td>
<td>20µm to 100µm</td>
<td>Air, water, oil</td>
<td>149 HV - 323.4 HV</td>
</tr>
<tr>
<td>900°C</td>
<td>8,10,12 hours</td>
<td>20µm to 100µm</td>
<td>Air, water, oil</td>
<td>166.4 HV - 345.9 HV</td>
</tr>
<tr>
<td>950°C</td>
<td>8 hours</td>
<td>20µm to 60µm</td>
<td>Air</td>
<td>185.9 HV - 366.2 HV</td>
</tr>
<tr>
<td></td>
<td>10 hours</td>
<td>40µm to 80µm</td>
<td>Oil</td>
<td>185.9 HV - 386.2 HV</td>
</tr>
<tr>
<td></td>
<td>12 hours</td>
<td>60µm to 100µm</td>
<td>Water</td>
<td>234.7 HV - 398.4 HV</td>
</tr>
</tbody>
</table>

Carburizing process can be followed by various heat treatments as a combinational method, so that mechanical properties can be improvised [5].

The carburized and tempered specimen shows a better result of 950*10^3 cycles for 200 MPa, whereas the carburized and austenized specimen resulted for 702*10^3 cycles. The crack growth rate decreases on the increasing temperature in tempering.[6].

Low carbon low alloy 20CrMnTi steel is quenched after heated at 930°C for 30 minutes, another case of same steel is heated at 930°C for 6 hours in atmosphere with carbon potential of 1.0% and then quenched in oil. The uncarburized specimen had tensile residual stress in the surface layer and compressive residual stress in the centre. Thus more compressive residual stress on the surface layer results in improved fatigue resistance [7]. It has a subsequent increase of tensile strength from 738MPa 959MPa [8].

Carburization treatment following few treatments were performed and results were obtained. The low carbon steel carburized for 5 hours at 900°C showed a better result of hardness value 104 RHB along quenching and a low value of hardness 52RHB along annealing which can be view from figure 1.[9]

![Fig. 1: Micro-hardness profile of carburized specimen.](image)

Alloy steels (AISI 8620, 9310 and 4140) were hardened using induction hardening, atmosphere carburizing and vacuum carburizing . The higher values of hardness were obtained for carburization of AISI 8620 and AISI 9310 alloy steels as 849HV and 776HV respectively. The AISI 4140 steel acquired the hardness of 632HV for induction hardening. Specifically vacuum carburization gives higher hardness value at greater depth than any other surface hardening methods [10-11].

For reducing the retained austenite and increase hardness, the carburized specimens alloy (SAE 4320 and a modified SAE 4122) were cold treated and the surface hardness also increased as expected due to reduction in retained austenite formation as shown in figures.1[12].

Carburized and uncarburized SCM420H steel material tested with ultrasonic torsional fatigue testing machine to obtain fatigue properties in high cycle regime. Both specimens failed for 10^7 cycles, but the carburized specimen is effective for enhancement of fatigue life [13].
The plasma carburization of steel DIN 17210 results in 25% increase in fatigue resistance in both low and high cycle region. But in case of low cycle region has a negative effect on service life. The fatigue strength reduces on reaching the strength of carbide layer, so it can’t hold for unsymmetrical push pull loading [14].

Another new process of pre nitriding (PreNitLPC) before carburizing was performed and compared with conventional ENDO process and low pressure carburization process. The nitriding process added its advantage along with carburization resulted in better improvement of mechanical properties. As normal carburization process at high temperature makes the grain size detoriates, but through PreNitLPC the grain size remains small on even rising temperature leading do improve in hardness effectively [15].

But even through low temperature carburization the increased surface hardness of 1200HV, which corresponds to greater than 70HR, retained ductility, residual compressive layer stress which has excess value of 2GPa in surface layer can be obtained [16].

For (A193-51T-B7) alloy steel the following heat treatments were conducted, namely annealing and quenching followed by tempering at 200°C. The fatigue crack growth rate of quenched and tempered specimen is lower than the annealing and tempered specimens[17].

B. Ion Nitriding, Boriding, Nitro Carburising and Annealing:

Through ion nitriding in AISI 4140 low alloy steel and subjecting to rotary bending test of 95 Hz, the result obtained as 50% improvement in fatigue strength depending on case depth and 12% improvement in fatigue strength comparing salt bath nitriding as shown in figure 10 [18].

Low nickel AISI 316LN austenitic stainless steel subjected to gas nitriding in the range of 400-5500°C resulted in improved mechanical properties of surface hardness value 1269HV whereas untreated sample has only 330HV [19]. For En-24 steel the plasma nitriding treatment was conducted and obvious result obtained as improved fatigue strength with increased hardness as shown in figure 11. A fact of compound layer of nitriding also found that up to 10µm or less than 10µm the fatigue property improves, but for compound layer greater than 10µm the fatigue property degrades as shown by S-N curve figures 12, 13, 14 and 15 [20].
Boriding is a diffusive heat treatment process like carburizing and nitriding in which boron compounds is diffused on the surface layer at 700-1000°C. The advantage is even high hardness of 1450-1500HV would be got at higher melting point, the hardness can be retained at higher temperatures and it has increased fatigue life and service performance under oxidation and corrosive environments. The hardness profile of boriding treatment is shown in figure 8. [21]
For small diameter C45 steels of 6mm diameter at 2MHz frequency obtained the hardness of 600HV near surface as shown in figure 17 [22].

Bainitically hardened steel subjected to combinational heat treatment of normalizing, soft annealing and hardening with altering combinations and parameters. Carbonitriding considered in treatment for a good hardness profile as shown in figure 9. [23].

CK45 steel treated with possible combination of heat treatments from normalizing (N), quenching (Q) and tempering (T) resulted the NQT has average hardness of 61.45HRA, NQ has 62.22HRA and Q has 62.92HRA. But parts without normalizing show shorter lives and more number of cracks in fatigue test [24].

SUJ2 steel material heat treated in a new way known as FA treatment involving double quenching after carbonitriding reduced the grain size half to that of conventional steel and improved the rolling contact fatigue life double that of carbonitriding treatments outcome [25]

The influence of the annealing heat treatment on fatigue life of two types of aluminium alloys was studied. The two alloys are mostly used in the aircraft because of their mechanical characteristics and their lightness. An increase in fatigue life was found by applying a specific heat treatment by maintaining temperature, time in furnace. This caused microstructural changes that creates the crack initiation during the fatigue testing. [26]

It is observed that the overall enhancement percentage of fatigue life of this alloy after the heat treatment is 31.86%. This result establishes that the artificial aging of alloy 7075 gives better enhancement than the natural aging of alloy 2024. The obtained results from the fatigue tests of all notched groups established that the fatigue failure begins from the surface at the region of stress concentration. [27]

The dual phase steel was created for improvement of fatigue strength and reduce surface hardening distortion. The compositions, formation of micro structure and influence of ferrite area fraction on heat-treatment distortion was studied. Improvement of fatigue strength by case hardening process was tested. Pitting fatigue strength was improved by 29% compared with conventional one. [28]
Table 2: Results of Fatigue strength based on Measures

<table>
<thead>
<tr>
<th>Measures</th>
<th>Effect to improve pitting fatigue strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change of steel</td>
<td>9%</td>
</tr>
<tr>
<td>Nitrogen added</td>
<td>6%</td>
</tr>
<tr>
<td>Vacuum atmosphere in heat treatment</td>
<td>6%</td>
</tr>
<tr>
<td>Double shot peening</td>
<td>7%</td>
</tr>
</tbody>
</table>

Investigations were carried out to study the effects of Tempering on the medium carbon steel. Samples were tested after heating at 900°C and maintained for 1 hr in a muffle furnace and quenched in oil. Experimental heat treatment (hardening and tempering) are done at 250°C increased by 100°C to 550°C for each tempering time interval. The tempered samples gave an increase in tensile strength and hardness than untreated samples. [29]

Nitrocarburizing of SAE 2205 duplex stainless steel conducted at 450°C using salt bath chemical surface treatment. At 8 hours of treatment, ferrite transformed to austenite and for extending time nitrogen diffusion becomes stronger resulting in hardness value of 1400HV (8 hours) which is 3.5 times of untreated material of hardness 396HV [30].

Ion nitrided properties of QT AISI 4340 low alloy steel studied and obtained 91% improvement of fatigue strength for 16 hours at 540°C with hardness value of 634HV. But prolonged nitriding reduces the mechanical properties due to increase nitride precipitates [31].

304, 316, 304L and 316L stainless steels undergoes nitrocarburizing for 560°C for time period of 2, 2.5, 3 hours and then oxidized for 1 hour. The results are shown in table 3 [32].

Table 3: surface hardness of stainless steels and their % increase in hardness.

<table>
<thead>
<tr>
<th>S.No</th>
<th>GRADE</th>
<th>SURFACE HARDNESS (HV)</th>
<th>Un-treated</th>
<th>Salt Bath Nitrided (180 min)</th>
<th>% INCREASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>304</td>
<td>220</td>
<td>870</td>
<td>395</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>304L</td>
<td>280</td>
<td>920</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>316</td>
<td>250</td>
<td>900</td>
<td>560</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>316L</td>
<td>280</td>
<td>1200</td>
<td>460</td>
<td></td>
</tr>
</tbody>
</table>

Nitried Nodular Cast Iron ferritic NCI involved gas nitriding treatment increase the fatigue limit, but scatters the fatigue life data with a hardness of 600 HV [33].

The iron sample developed a nitried layer two times thick than coarse grained sample under the same Gaseous nitriding conditions (500°C for 2 hr), to the fast diffusion of nitrogen along grain borders in the nano iron structure. Nitried layer of SMAT sample gave a high hardness and good resistance to wear. [34].

Formation of a thick nitried layer is used to enhance nitrogen diffusion in the surface layer. Nitrogen diffusion in nano crystalline materials is controlled by grain boundary.[35-36]

Fig. 10: Wear characteristics of nitride and un-nitrided
The application of gas nitriding on the tempered martensite steel 42CrMo4 has been studied and it was effective in improving the friction and wear resistance compared to the base metal. Nitriding improves the adhesive wear resistance.[37].

Nitrided layer hardness is not directly related with residual macro stresses. Also the increase of fatigue limit is not related with the thickness of layer. The efficiency of nitriding depends on many interconnected factors such as technology, composition of steel, level of residual macro and microstresses, hardness, depth and structural composition of nitrided layer.[38].

The iron nitriding increases fatigue strength of all structural steels by nitrogen and causing compressive stresses. Fatigue limit of steel after ion nitriding increases up to 80 %.[39-40].

C. Aустемперирующий:

It is the general treatment for ductile irons involving heating from 875-900ºC following quenching in salt bath or hot oil resulting for improvement in properties like tensile strength of 1220MPa [41]. Austempered Ductile Iron (ADI) undergoes austempering at 300ºC forms a lower amount of retained austenite with hardness 462HV, but on prolonged heating higher amount of retained austenite is obtained, causing higher ductility and lower strength of ADI [42].

Austempered Ductile Iron (ADI) undergoes annealing and normalizing quenching and tempering; austempering with and without copper shows the strength and hardness was more with copper whereas ductility is more for without copper [43].

D. Nitriding:

Fatigue testing under fully reversed axial loading (R=−1) and zero-to-tension axial loading (R=0) was done on AISI 4140 gas nitrided specimens. Fatigue life improvement brought by nitriding becomes fully effective when cracks initiate and propagate at the surface.[44]. The residual stress induced induction heating in the SS specimens increases the HCF lives. [45]

In order to clarify the effects of nitriding and hybrid surface modification process on fatigue properties of SCM435H steel, high cycle fatigue tests were done using rotational bending machine at room temperature. Rotational bending high cycle fatigue tests (R=−1) were carried out at room temperature for SCM435H steel treated with nitriding and hybrid surface modification. The hybrid surface modification process in this study is highly effective in increasing the fatigue strength. [46]

Fig. 11: Schematic illustrations explaining the difference of fatigue strength with the fracture mode transition

The hybrid surface treatment was composed of plasma nitriding and fine particle bombarding (FPB). The hybrid surface treatment greatly improved the fatigue strength.[47]

A structural component can influence the Fatigue resistance by environmental, mechanical variables and metallurgical effects [48]. The major reason of reduction in fatigue limit is by the defects on surface of high strength steels [49]. Crankshaft manufacture in Automobile industry is mostly done using EN8 steel for good strength and toughness. Fatigue failure is the defect to the components experiencing repeated loads [50]. Surface treatments can enhance the fatigue behaviors.

Nitriding causes low Distortion, reduced Grinding and finishing, temper Resistance. Induction heating gives the effect of consistency, product quality and environmentally good.

The fatigue strength is improved approximately 50% with t case depths and 12% of fatigue strength is reached with respect to liquid nitriding specimens [50]. Nitrided samples gives resistance on scuffing comparing with the base metals, the nitride specimens give wear resistance and improve the life [51]. The plasma nitriding improves fatigue strength and life of the material with layer of 10μm [52].
The fatigue strength of AISI 4340 steel was raised up to 91% by the process of ion nitriding [53]. The residual stress caused by induction heating in the SS specimens increases the HCF lives [54]. Fatigue strength of hybrid surface modification process was much higher than substrate and nitride specimens [55].

E. Hybrid Treatments:

The heat treatment process such as nitriding and induction hardening was taken and few mechanical tests were done. Fatigue strength of heat treatment had increased [56]. Nitriding process improves all mechanical properties and also its specific feature in fatigue strength. Micro hardness was improved due to properties modification. Corrosion and wear resistance were increased by nitriding process [57].

To clarify the effects of nitriding and hybrid surface modification process by combining (nitriding and induction hardening) on fatigue properties of SCM435H steel, high cycle fatigue tests were done on a rotational bending machine at room temperature. It was revealed that hybrid surface modification process created compressive residual stress and hardened even at center of the specimen. Fatigue strength of hybrid surface specimens was much higher than substrate and nitrided specimens. This was because a transition of fracture; fatigue fracture of nitrided specimens happened at inside of the layer, in hybrid surface modified specimens, fatigue crack initiated at the surface with higher hardness and compressive residual stress.[58]

The dies are subjected to a QT followed by plasma nitriding, gas nitriding. The core with low hardness (500-550 HV) gives enough toughness, while the surface treatment produces a case depth of 0.20 - 0.50 mm and a hardness of up to 1200 HV, that yields the wear and the fatigue resistance. The compound layer (around 4-10 μm) is reason for good tribological and corrosion properties of the die surface.[59]

Conclusion:

- The tempered samples gave an increase in tensile strength and hardness than untreated samples
- In Nitro carburizing of steel, ferrite transformed to austenite at 500°C and for extending time nitrogen diffusion becomes stronger resulting in hardness value of 1400HV (8 hours) which is 3.5 times of untreated material of hardness 396HV
  - Micro granular structure of the material should have to be fine sized through heating methods. Further reduction in grain size of the material increases the fatigue strength. Hence heating method should consider micro granular structure. On hardening materials through heating, it has been observed that the hardness value gradually decreased on the increasing depth of material; hence in most cases proper surface hardening is followed to increase the fatigue strength.
- Through ion nitriding in steel 50% improvement in fatigue strength is obtained depending on case depth and 12% improvement of fatigue strength than salt bath nitriding. It has even high hardness of 1450-1500HV can be obtained at high melting point, the hardness can be retained at higher temperatures and it has increased fatigue life and service performance under oxidation and corrosive environments.
- Nitriding treatment appreciably improves the adhesive wear resistance and also grain size remains small on even rising temperature leading do improve in hardness effectively.
- Gaseous nitriding (500°C for 2 hr), which is attributed to the fast diffusion of nitrogen along the grain borders in the nano iron..Nitrided layer of SMAT sample showed a high hardness and good wear resistance.
  - Dual heat treatment or heat treatments combined with an additional surface modification method are used to meet special property needs and the required applications. In major cases, carburizing and nitriding are processed in various conditional parameters and experimental methods to give better results than others.
  - Combining carburizing and nitriding process in series can have better result of mechanical properties.
  - Hybrid surface modification process by combining (nitriding and induction hardening) on fatigue properties of SCM435H steel revealed that this process created compressive residual stress and hardened even at the center of the specimen. Fatigue strength of specimens was much higher than that of substrate and nitrided specimens.

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