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# Comparison of Surface Hardening Processes Applied to AISI 5140 Steel with Side Load Test

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**Research Article**

**Abstract**

AISI 5140 Tempered steel is generally preferred in the joints of vehicles. This steel is a material with high toughness. Its usage areas are quite wide. The purpose of the surface hardening process is to increase the wear resistance of surfaces exposed to wear, as well as to increase the fatigue life of the part and increase corrosion resistance. Since the inner parts of the parts are not affected by surface hardening, the resistance to impacts increases and therefore the formation of cracks on the surface is delayed. Surface hardening processes delay the formation of cracks on the surface and extend fatigue life. In this study, a comparison was made between a part with induction surface hardening, which is one of the methods in which the chemical composition of the surface is not changed, a part with nitration, which is one of the methods in which the chemical composition is not changed, and a part with standard reclamation heat treatment. Side Load test, a static testing method, was used for this comparison. In the Side Load test, the samples were compressed from the conical region and a vertical load was applied corresponding to the center of the joint. According to the results obtained in the tests, the sample with Induction surface hardening process withstood 64500 N, the sample with Nitriding heat treatment withstood 54500 N and the sample with Standard tempering heat treatment withstood 50200 N. According to the results obtained, the sample with the highest durability rate is the sample whose surface was hardened by induction.

*Keywords*: AISI 5140; Induction; Nitration; Side load test.

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## 1. Introduction

For a machine part that is thought to be manufactured, first of all, the most suitable material for that element is selected for the working conditions. In material selection; easy shaping, physical, chemical and mechanical properties are judged whether they will be suitable. Surface hardening methods play an important role especially in improving the surface properties of metal materials.

Surface hardening processes are applied to machine parts in cases where a ductile core is desired for the surface to be hard and wear resistant and at the same time to resist impacts. The most advanced and recently developed coating and surface-hardening technologies make it possible to obtain almost the full range of physical–mechanical and crystal–chemical properties of the metalworking tool surface and electronic component surface for a wide range of applications to enlarge product operational life for working under the most extreme mechanical and thermal loads The main purposes of surface hardening processes are to increase the fatigue life of the part, to increase the wear resistance of the surfaces exposed to wear and to improve the corrosion resistance.

Surfaces that are not intended to be affected by hardening processes are covered with a special paste, paste or clay. In many machine elements such as gear wheel surface, bolts, trunnions, shafts, pin bearings, the desired wear and crushing resistance is achieved by hardening only the surface layer, the thickness of which is mostly 0.1-2 mm, while the inner parts remain tough. [1-4]

Surface hardening is one of the main ways to increase the wear resistance of parts and frictional units. In industry, there are more than a hundred methods of surface hardening, but not all have found industrial application. The most well-known methods include carburizing, nitriding, surfacing, and boriding. Surface hardening methods can be classified into 2 main categories. The first category is the processes in which the chemical structure of the surface is changed. The second category is the processes in which the chemical structure of the surface is not changed. The first category is in itself; It is divided into 3 classes: Carburization (Carbonation, Cementation), Nitriding (Nitrification, Nitriding), Carbo-Nitriding. The second category is in itself; It is divided into

4 classes as Flame Hardening, Induction Surface Hardening, Immersion Method Surface Hardening, Electron Bombardment and Laser Hardening. [5]

In this study, Nitration, one of the processes in which the chemical structure of the surface is changed, and surface hardening with Induction, one of the processes in which the chemical structure of the surface is not changed, were also studied on untreated samples. A comparison study of three different surface hardening methods was made.

Improved steels are suitable for hardening in terms of chemical components and carbon content. At the end of the reclamation process, they show high toughness at a certain tensile strength. Among the DIN 41Cr4 (SAE 5140) tempered steels, they have a significant use in the automobile industry. In steel; While chromium increases corrosion and oxidation resistance, hardenability and high temperature strength, molybdenum increases strength, hardness, wear resistance and toughness. [6]

The curing process is defined as a combination of first hardening and then tempering processes, which will eventually impart high toughness to the steel part (Figure 1). Due to the superior mechanical properties, they acquire at the end of the treatment process, curing steels are used in the manufacture of parts such as various machine and engine parts, forging parts, various bolts, nuts and studs, crankshafts, axles, control and drive parts, piston rods, various shafts and gears. are used in a wide area. [7]

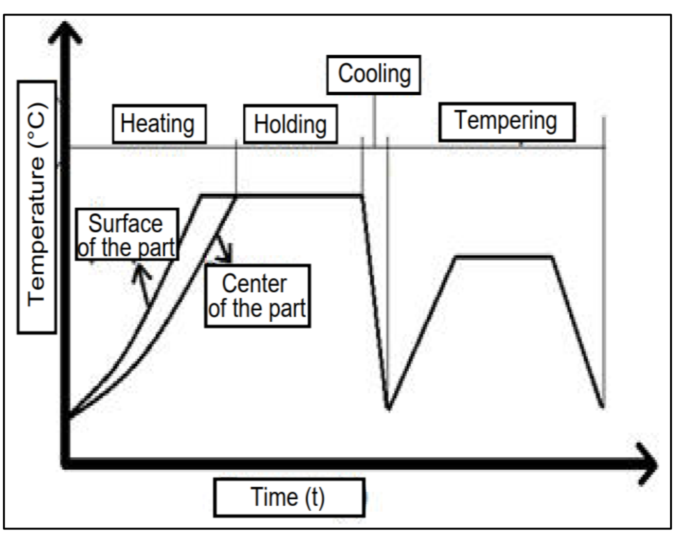


Fig. 1. Schematic representation of the breeding process

Hardening is the most important heat treatment that gives properties to steels. The hardening process is the process of firstly heating the steel part to the austenite phase temperature and keeping it at this temperature for a certain period of time and cooling it rapidly in a suitable environment. The holding time at the austenite temperature determines the homogeneous structure of the steel part in the austenite phase. It is then hardened by rapid cooling. The main purpose of hardening is to obtain a completely martensite structure at the minimum cooling rate. The minimum cooling rate that will give a completely martensite structure is called the critical cooling rate. The critical cooling rate depends on the chemical composition of the steel and the austenite grain size. If the steel part is cooled faster than the critical cooling rate, the result is a high hardness only martensite structure. However, if it is slower than the cooling rate applied to the part, the amount of martensite in the structure will decrease and the hardness value will decrease, as some or all of the austenite will turn into ferrite and pearlite. As the difference between the cooling rate of the part and the critical cooling rate increases, the amount of austenite to ferrite and pearlite conversion will increase and accordingly the hardness will decrease. [8]

### 1.1. Induction Surface Hardening Method

Discovered by Michael Faraday, induction begins with a coil made of conductive material (such as copper). The general view of the surface hardening process by induction is given in Figure 2. The functionality of the magnetic field varies depending on the coil design and the amount of current flowing through the coil. Depending on the direction of the current, the direction of the magnetic field also changes, so the alternating current passing through the coil will cause the direction of the magnetic field to change at the same rate as the alternating current frequency. 60Hz AC current causes the magnetic field to change direction 60 times in one second. 400kHz AC current causes the magnetic field to change direction 400,000 times in one second. When a workpiece of conductive material is placed in a changing magnetic field, it induces voltage in the workpiece (Faraday's Law). The induced voltage also leads to the flow of electrons, i.e. current. The current flowing in the workpiece is in the opposite direction to the current in the coil. This means that we can control the current in the workpiece by controlling the frequency of the current in the coil. When current flows through a material, a resistance is created against the movement of electrons. This resistance manifests itself as heat (Joule Heating Effect). Materials that are more resistant to electron flow will generate higher heat when current flows through them. However, it is also possible to heat highly conductive materials (such as copper) using induced current. This phenomenon is critical in induction heating. [9]

In the induction hardening method, an induction coil fed with a high frequency current is placed around the part to be hardened. And as the frequency induced in the part increases, these regions heat up due to the resistance of the material to the eddy currents concentrated near the surface. In this method, the shorter heating time reduces the possibility of warping, cracking and grain coarsening. The method can be easily and precisely controlled and is very conducive to automation. Since the investment cost is high, it is economically necessary to have a large number of processing parts.

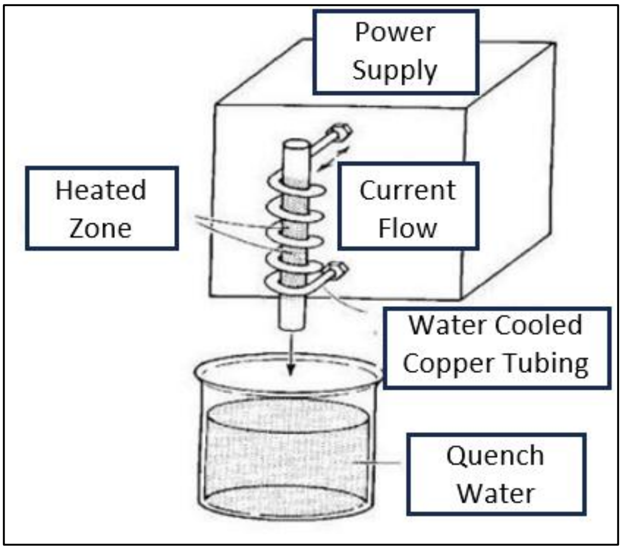


Fig. 2. Surface hardening by induction

### 1.2. Nitriding Surface Hardening Method

Nitride-forming elements belong to the IV a, V a, and VI a family of the periodic table, and the elements in this group can be easily hardened by nitriding method. Therefore, surface hardening by nitriding is only possible for steel and nickel alloys alloyed with some nitride-forming elements. In the nitriding of these alloys, nitrogen atoms diffuse from the surface into the material and form a hard nitride layer by reacting with the alloying elements. [10]

Alloying elements such as Al, Cr, Mo, V used in steels are the most effective elements in forming nitrides. Adding Mo reduces the risk of brittleness at the nitriding temperature. Other alloying elements such as Ni, Cu, Si and Mn have less influence on the nitriding properties. Al is a very strong nitride-forming element. This effect is particularly evident in steels containing Al (0.85-1.5% Al) and provides very good nitriding results. Also, V is a really strong nitride builder. [11]

In the surface hardening process with nitration, the increase in hardness is achieved by spreading the nitrogen atom on the surface of the part at temperatures below its temperature (500-580°C) and forming a nitride layer on the surface. The hardness of the part does not increase with the transformation of austenite to martensite. In order for the method to be applicable, approximately 1% of the steel must be alloyed with suitable nitriding agents such as Al, Cr and Ti. Since aluminum, chromium and titanium have a higher affinity for nitrogen than iron, an AlN, TiN, CrN layer with a hardness of about 1200 HV is formed on the surface. Since the austenite temperature is not reached in nitriding, martensite does not form during cooling. Since it is carried out at lower temperatures, no/very little distortion or deformation occurs.

Nitriding surface hardening method is divided into three classes as liquid, gas and plasma. In this study, gas nitration method was preferred. The gas nitration process takes place in ammonia gas. Processing temperature is 510-550°C. The released atomic nitrogen diffuses into the steel. The nitriding time required for the nitriding depth to be 0.5 mm is approximately 50 hours. In high-speed steel tools, forming a layer with a thickness of about 0.02 mm in nitration time in the bath under the tempering temperature is sufficient to significantly increase the resistance against softening due to heat during operation and the tool life.

The nitriding surface hardening process has significant advantages over parts. Reasons such as high surface hardness, increased wear resistance, increase in fatigue life, increase in corrosion resistance, absence of thermal distortion can be given as examples. The surface layers of nitride materials are divided into three parts. The top layer is the “white (com-pound) layer” with high nitrogen content, the “diffusion layer” below it, and the “nuclear region” at the bottom layer. The white layer is the region with the highest nitrogen content and appears as a white layer in the metallurgical (light) microscope when etched with nital. This layer is a brittle and brittle layer, which is desirable in many applications. When it comes inwards from the surface, the percentage of nitrogen also decreases and the white image under the microscope is replaced by the normal needle nitride image. As we move towards the inner parts of the steel, the amount of nitrogen gradually decreases, finally reaching the core region where nitrogen does not reach. There is a transition zone between the core region and the diffusion layer.

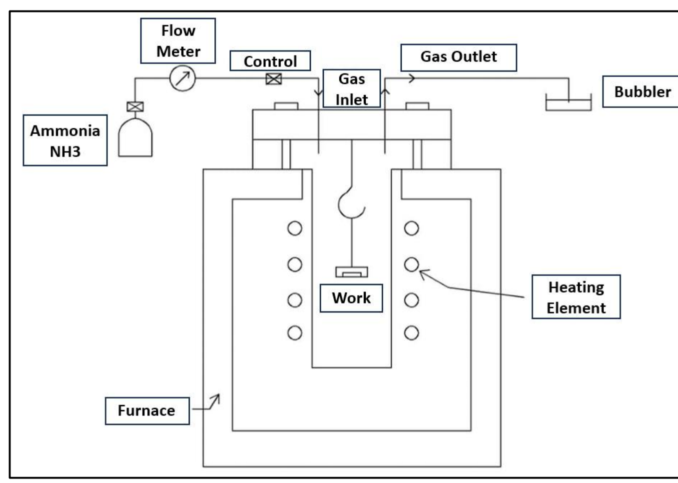


Fig. 3. Nitriding process chart

### 1.3. White Layer Properties

The outermost nitride layer, the white layer, gets its name because it appears white after etching with nital (3-5% HNO3 + alcohol). The white layer, which can be allowed to form up to 20 μm thick by adjusting the nitriding conditions and time, is hard, brittle and resistant to abrasion. In case the thickness is increased more; It is known that cracks may occur in the layer and this will adversely affect the fatigue strength. In the white layer, γ' (Fe4N) and ε (Fe2N and Fe3N) phases or a mixture of these can be seen. γ ' (Fe4N) has a face-centered cubic (YMK) structure, while ε (Fe2-3N) has a hexagonal structure. The fact that the white layer consists only of these intermetallic compounds ensures that its hard-ness is independent of the chemical composition of the material. In addition, the mechanical properties of the white layer are highly dependent on the amount of these phases and the thickness of the layer. The formation of the γ' (Fe4N) phase in the white layer is preferred in applications with low abrasion resistance and impact resistant due to its softness and ductility, while the formation of the ε (Fe2-3N) phase is preferred for parts with high abrasion resistance. [12]

In the formation of the white layer, the thickness, type and number of the phases play an important role in determining the properties. The gas composition and phase types used during ion nitriding are the main variables. In ion nitriding, atom bombardment plays a major role in nitride formation. Due to this process, a white layer is initially formed on the surface. The white layer thickness creates a different layer on the surface as a result of the process with nitrogen gas or nitrogen-hydrogen gas combination. [13]

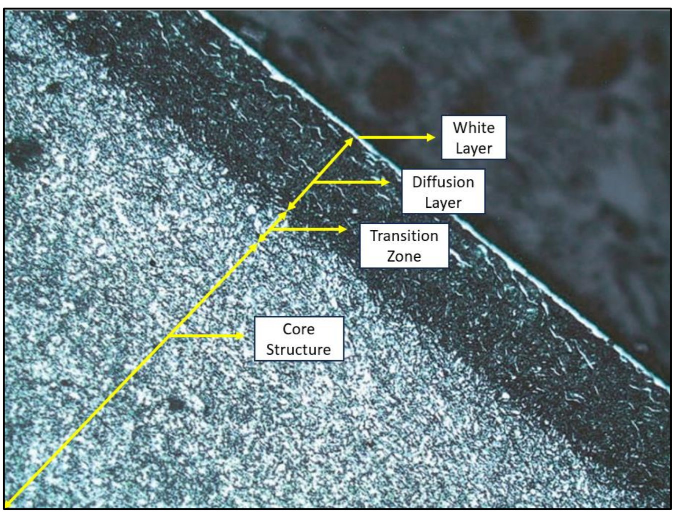


Fig. 4. Microstructure image of part surface section after nitration heat treatment

### 1.4. Side Load Test

Side load test is a type of test that can be applied to steering or suspension joints. The purpose of the test is to determine under which load conditions the joint will receive a permanent set without breaking. The test fixture is given in Figure-5. A small flat piece is ground at the head of the joint so that the reading of the dial indicator or other measuring device is accurate. The comparator or any measuring device is placed from the grinding area as shown in Figure-5. The apparatus is designed to hold the joint conical fully. The conical apparatus is also connected to the test apparatus as seen in Figure-6. The comparator or any measuring device is calibrated and zeroed prior to testing. The load to be delivered must pass through the center of the joint.

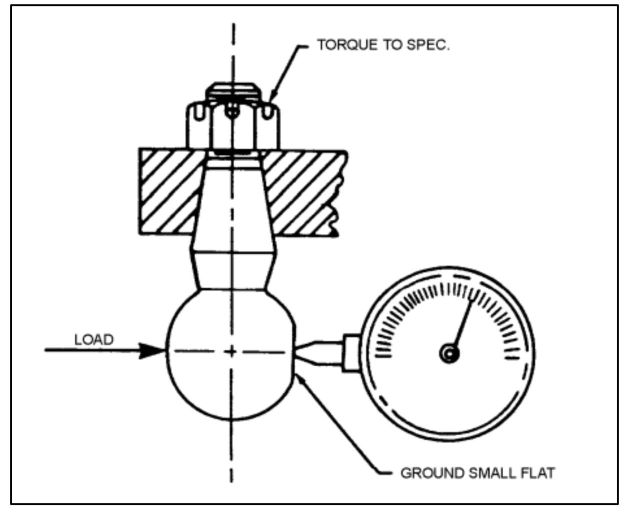


Fig. 5. Test fixture

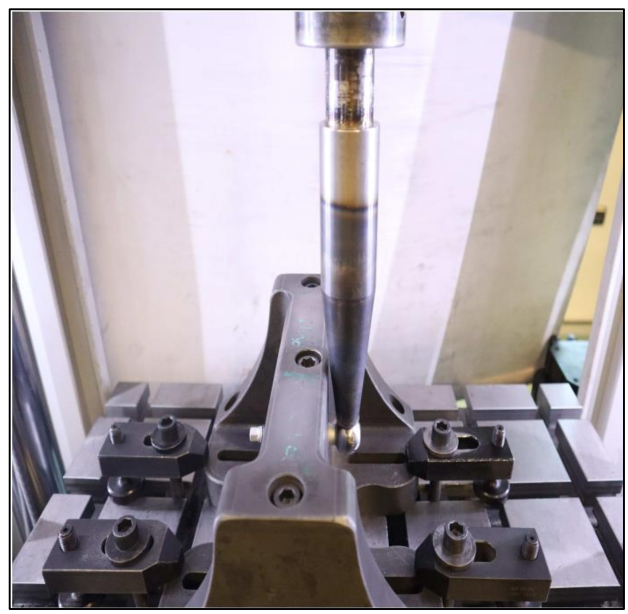

Fig. 6. Test connection image

In side load tests, the relationship between stress and strain is examined in the elastic and plastic regions of the material. Yield strength is considered as a single number or point on the curve. In reality, however, there is a small transition zone be-tween the elastic and plastic region; This is not an instant transition. Therefore, yield strength is defined using a 0.2% cut from the elastic line and plotting its intersection on the stress/strain curve as shown in Figure 7. In the plastic region of the material, the part is permanently deformed and does not return to its original shape when the stress is released.

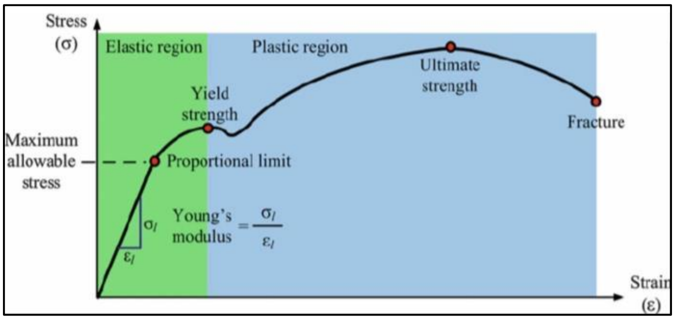


Fig. 7. Relationship between stress and strain in the plastic and elastic regions of the material

## 2. Main Section

### 2.1. Material Properties of Test Samples

ANSI 5140 tempered steel was used as test material. ANSI 5140 tempered steel is a type of alloy steel known for its high strength and hardness properties. This type of steel contains chromium as an alloying element. This element helps the steel to harden and gain high strength. In addition, 5140 tempered steel stands out with its excellent machinability. Thanks to these properties, it is frequently used in many sectors such as automotive, energy, manufacturing, machine and tool making. 5140 tempered steels can be hardened to reach different hardness levels. These hardness levels can be customized according to the usage areas of the steel. For example, higher hardness levels are used in the manufacture of impact resistant parts, while lower hardness levels are used in the manufacture of parts with higher bearing capacity. The chemical analysis of the test material is given in Table-1.

Table 1. Chemical compositions of the joint used in the study

| | C | Si | Mn | P | S | Cr |
|---|---|---|---|---|---|---|
| AISI 5140 | 0,37 | 0,21 | 0,71 | 0,01 | 0,01 | 1,00 |
| Standard 5140 (1.7035) | 0,38-0,45 | ≤0,4 | 0,6-0,9 | ≤0,025 | ≤0,035 | 0,9-1,2 |

After cutting 90 mm long pieces from 32 mm diameter AISI 5140 alloy hot drawn profile, a joint piece with a spherical connection piece was obtained by heating with induction and hot forming (hot forging) method. It was heated to a temperature of approximately 900℃ with the induction heating method and shaped by the closed die forging method. A total of 30 shapings were made from this piece for this study.

30 pieces were made with post-forging treatment heat treatment. 10 pieces were surface hardened by induction and the remaining 10 pieces were nitrided surface hardened heat treatment. Surface hardening was not applied to the remaining 10 pieces. Breeding heat treatment; Hardening was carried out by cooling in oil from austenitizing temperature of 880°C in a controlled atmosphere furnace. It was kept in the oven for 2 hours in order to obtain a hardness range of 26 HRC – 32 HRC at 450°C tempering temperature.

Surface hardening heat treatment by induction; It was carried out in the Inductotherm brand device with a power of 388V 50Hz 118kW, which is also used in the current process. After heating is done in approximately 25 seconds, the surface hardening process is completed by cooling water at 24°C in 9.5 seconds

Surface hardening heat treatment with nitration is carried out in furnaces under vacuum with gas nitration method. It was carried out by permeating the surface of the part with nitrogen for 3 hours at a temperature of approximately 520°C.

### 2.2. Hardness Analysis

The hardness measurement was measured with a mikrovickers hardness tester under a load of 30 g and a dwell time of 20 seconds. The hardness results are given in Table 2. The hardness distribution was analysed by measuring from the surface of the part to the center of 2 mm at 0.2 mm intervals.

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Table 2. Hardness measurement results

| Hardness (HRC) | Induction | Nitration | Standard Breeding |
|---|---|---|---|
| 0.2 | 54,8 | 45,4 | 28,4 |
| 0.4 | 56,9 | 32,2 | 27,5 |
| 0.6 | 56,3 | 27,9 | 28,1 |
| 0.8 | 57,8 | 27,2 | 29 |
| 1.0 | 54,2 | 26,8 | 28,5 |
| 1.2 | 53,4 | 27,5 | 29,2 |
| 1.4 | 54,8 | 27,3 | 27,4 |
| 1.6 | 47,7 | 28,8 | 28,5 |
| 1.8 | 28,1 | 28,9 | 28,1 |
| 2.0 | 28,2 | 28,5 | 28 |

### 2.3. Microstructure analysis

Standard metallography sample preparation steps were performed for the ANSI 5140 steel alloy part. Standard metallography techniques; Coarse and fine sanding was done with SiC sandpaper and polishing with 3-micron diamond suspension. Then, a mixture of nital (2% HNO3 and 98% alcohol) was prepared and the etching process was completed by keeping the pieces in this mixture for about 9 seconds. Microstructure checks were performed on the NIKON MA 200 Optical microscope. In Figure 8, the structural images of both nitrated, induction and cured joints are given. In these images, both surface and central controls were made. Center 500X microstructure images for all parts confirm the curing heat treatment of the parts.

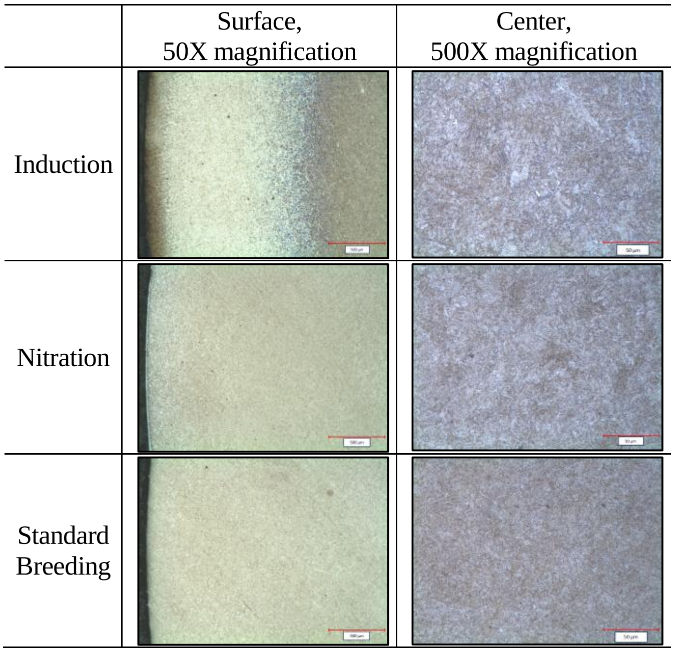


Fig. 8. Microstructure images of test specimens

The induction depth was observed in the microstructure as a maximum of 1.4 mm in the part to which induction surface hardening heat treatment was applied. As a result of the hardness analysis, it is observed that there is a decrease in hardness after 1.4 mm. Thus, microstructure and hardness analysis confirm each other. The microstructure image containing the hardness distribution supports this situation as seen in Figure 9.

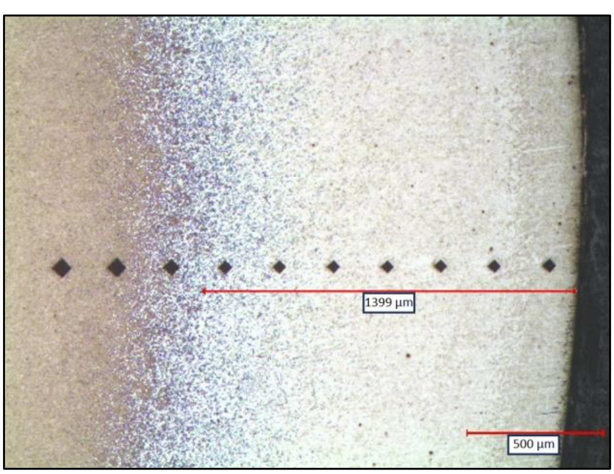


Fig. 9. Microstructure image of induction depth of induction part

The nitration depth was observed in the microstructure as a maximum of 0.2 mm in the part to which the nitriding surface hardening heat treatment was applied. As a result of the hardness analysis, it is observed that there is a decrease in hardness after 0.2 mm. Thus, microstructure and hardness analysis confirm each other. The microstructure image containing the hardness distribution supports this situation as seen in Figure 10. In addition, the average white layer thickness in the nitriding surface hardening process is 13.71 µm. In Figure 10, the hardness distribution of the nitride part and the microstructure image of the white layer measurement are given.

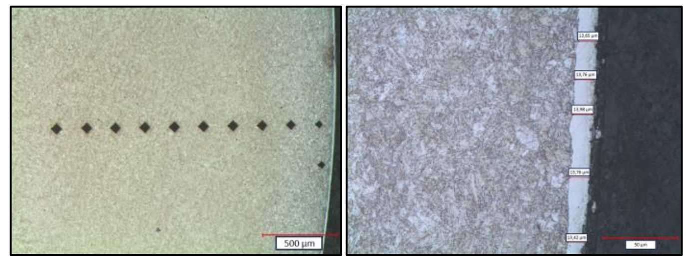


Fig. 10. Microstructure image of nitride part including hardness distribution and white layer thickness

## 2.4. Side Load Test Results

### 2.4.1. Standard Breeding Process Sample Test Results

In materials, yield strength is considered as a single number or point. The yield strength as a result of the side load test is defined by using a 0.2% cut from the starting point on the resulting graph and plotting its intersection on the stress/strain curve. The side load test result graph of the standard repaired joint is given in Figure 11. The images of the fracture formed in the sample after the test are given in Figure 12. The fracture surface image of the fracture surface formed in the joint after the test under the microscope is given in Figure 13.

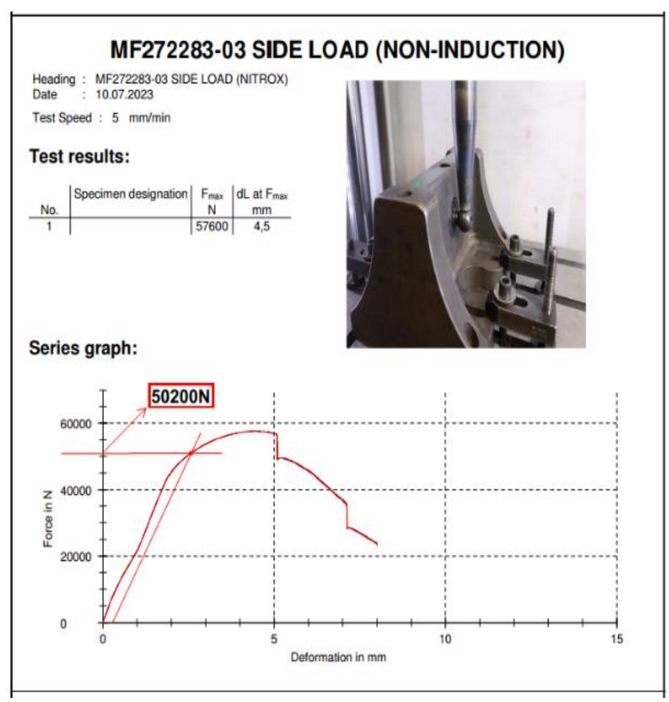


Fig. 11. Test result graph of joint with standard improvement treatment

Fig. 12. Broken images of with standard treatment process

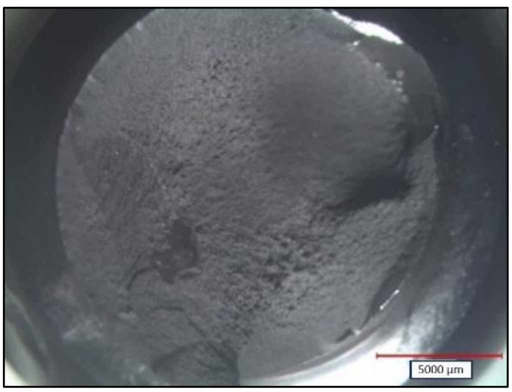


Fig. 13. Fractured surface image of the standard treated joint under the microscope

### 2.4.2. Sample Test Results with Nitriding Process

The result graph of the side load test applied to the nitride surface hardened sample is given in Figure 14. The images of the fracture formed in the sample after the test are given in Figure 15. The fracture surface image of the fracture surface formed in the joint after the test under the microscope is given in Figure 16.

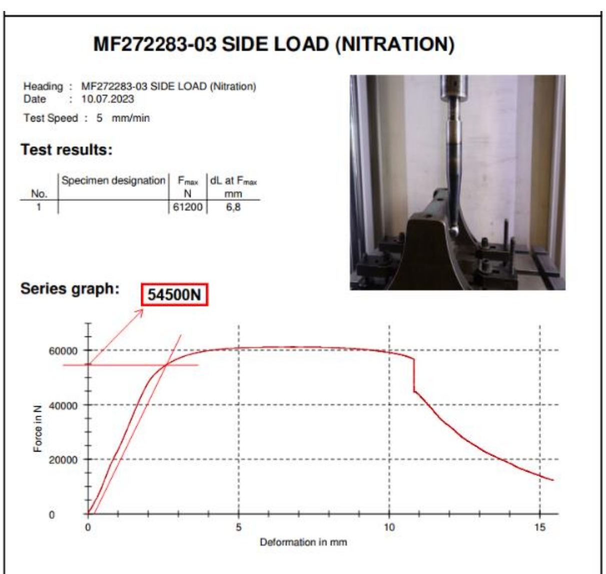


Fig. 14. Test result graph of nitride joint

Fig. 15. Broken images of nitration treated joint

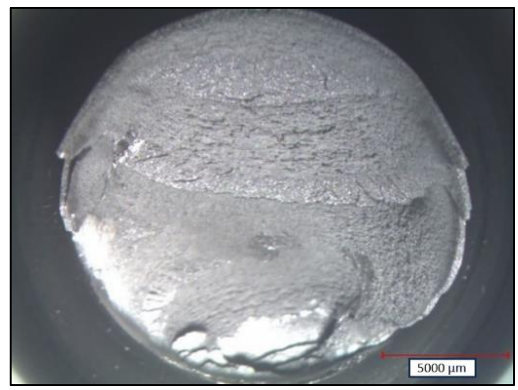


Fig. 16. Broken surface view of nitride joint under microscope

### 2.4.3 Sample Test Results with Induction Process

The result graph of the side load test applied to the induction surface hardened sample is given in Figure 17. The images of the fracture formed in the sample after the test are given in Figure 18. The fracture surface image of the fracture surface formed in the joint after the test under the microscope is given in Figure 19.

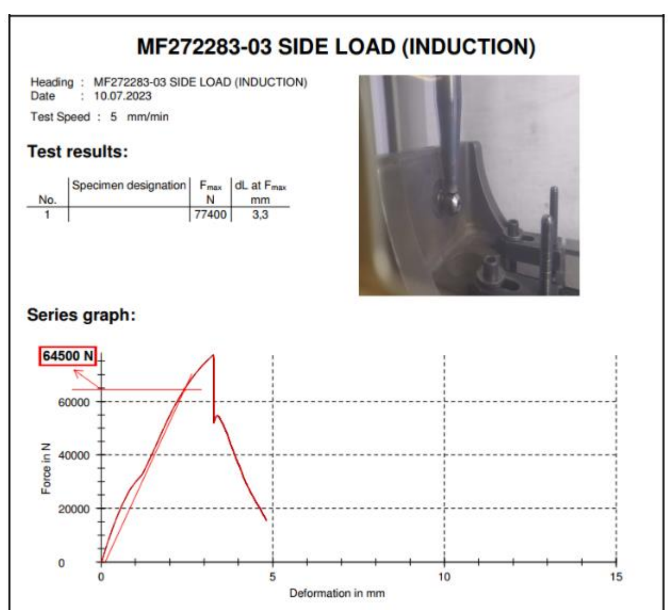


Fig. 17. Test result graph of induction treated joint

Fig. 18. Broken images of induction treated joint

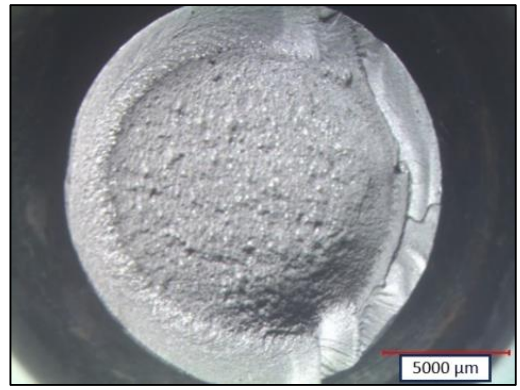


Fig. 19. Broken surface view of the induction treated joint under the microscope

## 3. Conclusions

The fracture surface image of the induction hardened part shows the induction depth. As can be seen from the fractured surface images of all samples, the sample with the lowest strength ratio compared to the others is the sample with standard improvement heat treatment. The part with nitration heat treatment is more ductile than the part with induction heat treatment. In this case, the most durable part was the sample with induction surface hardening.

In the side load test results, the points where the parts enter permanent deformation were determined. The standard heat-treated part transitioned from the elastic region to the plastic region at 50200 N, the nitrided surface hardened part at 54500 N, and the induction hardened part at 64500 N. In line with these results, the most durable part was the part with induction surface hardening. In the side load test, it is expected that this part will not undergo permanent deformation before 60000 N. The only sample that met this requirement was the part that had been treated with induction surface hardening. The surface hardness of the induction treated sample is 56 HRC on average. The surface hardness of the nitrated sample is 31 HRC on average. Since all parts are treated with heat treatment, the average hardness values of the center are 28 HRC. In the direction of these values, if the surface hardening hardness value is produced according to a hardness value such as 55 HRC, it will provide the expected condition.


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### Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

### CRediT Author Statement

**Talha İkbal Çığır:** Conceptualization, Investigation, Methodology, Project administration, Resources, Writing-original draft, Writing-review & editing
**Ahmet Asım Eser:** Conceptualization, Validation, Source research, Testing, Draft checking, Consultancy.
**Furkan Göğer:** Funding acquisition, Resources, Testing, Writing-review & editing.
**Mustafa Acarer:** Supervision, Consultancy, Resources, Writing-review.

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