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The Effect of Heating Time in Induction Hardening Process on the Hardness Profile of a Ball Stud: A Case Study

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Research Article

Abstract

The induction hardening method is widely used for the surface hardening of industrial products to improve the resistance of the material to various failure modes such as fatigue, wear, etc. Hence, surface hardening of parts that undergo repetitive forces and that work in close contact with other moving components plays a significant role in their service life. In this study, an automotive ball stud part, which is a highly prone part to fatigue and wear failures, has been induction hardened for varying amounts of heating time (2s, 3s, 4s and 5s) under constant power (135 A) and frequency (50 Hz). The hardness, the hardness depth and the microstructure of the parts have been investigated utilizing hardness tests and optical microscopy. Additionally, the effect of different cooling durations (3s, 5s, and 7s) and the resistance of the parts to the bending force has also been examined. The results show that the increase in heating time has an increasing impact on the hardness of parts and the hardness depth. The bending forces have also been shown to be increasing by increasing the heating time. The highest hardness level, hardness depth and bending resistance have been found when induction heating the specimens for 5s. Increasing the cooling time has not led to a considerable variation in the hardness profile of the specimens.

Keywords: Ball stud; Hardness profile; Hardness; Induction hardening

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1. Introduction

The induction heating method is an effective method for heating the specimens within a significantly short period of time for considerably low energy expenses. It has a wide range of applications for industries like aerospace, automotive, healthcare, etc., [1–4]. Among these, the main industry that the induction heating method is mainly used is the automotive industry. The induction heating method could be used for welding parts [5,6], in heat treatment processes [7], in hot forming [8], and warm forming [9], processes, and for surface hardening [10].

Although surface hardening of parts could be achieved by many methods such as carburizing, nitriding, and shot-peening, the induction hardening method stands out due to the capabilities like hardening the surface in a short time, hardening only a fraction of a part such as gear teeth, ability to temper the parts after the hardening and so on [11]. Surface hardening by induction heating method is provided by heating the specimen above the austenitization line (A_3) and then fast cooling to transform the austenite structure into the martensite structure [11]. Due to the fast heating of the specimen, only a fraction of the surface of the specimen is heated to the temperatures above the A_3 line, and in this way, only a thin layer of the surface of the specimen is hardened while maintaining the mechanical properties of the base material at the core of the specimen [12]. The thickness of the hardened layer and as well as the hardness level of the hardened layer, however, are dependent on a number factors such as the induction power, frequency, heating time and cooling rate [13,14]. In a study carried out by Rokicki et al. [13], the researchers have investigated the effect of different induction voltage levels (300V, 400V, 500V, 600V) on the hardness profile of 41Cr4 steel and 36NiCrMo16 steel. The researchers have found out that the 300V level hasn't been sufficient to harden the both steels, however, with the increase of voltage level, the thickness of the hardened layer has increased up to 6 mm depth. Shtarbakov et al. **[14],** have carried out numerical simulations to observe the temperature distributions occurring during the induction heating process with different power and exposure times for 41Cr4 steel and experimentally conducted a hardening process to check the numerical model. They have shown that the temperature levels has risen up with the increase of induction power and the exposure time and, in the experimental results, they have observed that the thickness of the hardened layer has increased with the increase of exposure time. Rathinasuriyan et al. [15], have applied different pre-heat treatment processes (annealing, normalizing, normalizing + hardening and tempering) to the EN8 steel and then surface hardened the specimen by induction hardening to investigate the effect of initial pre-heat treatment processes on the hardness profile of EN8 steel. They have shown that the pre-heat treatment process; normalizing + hardening and tempering has exhibited the highest hardness level as compared to the other pre-heat treatment processes. Other than the induction heating process parameters, the properties of the material such as the chemical composition and the initial microstructure also have considerable impact on the hardening response of the material. Wendel et al. [16], have investigated the initial microstructure and the alloying elements on the hardening response for different steels. They have indicated that the alloying with silicon and manganese has reduced the amount of non-martensitic transformation after hardening.

Surface hardening has many advantages in terms of fatigue life and wear resistance [17–21]. These terms becomes even more important for especially components like ball studs which bears repetitive forces and works with other components in close contact. Ball studs are used in suspension systems in the automotive industry to let the wheels of the vehicle to move in the vertical direction. Hence, repetitive forces are continuously exerted on the ball studs during its service and, wear occurrence can be observed at the ball socket region of the ball stud as shown in Figure 1. A fracture occurrence on this component in an automotive suspension system could lead to the loss of vehicle control and have cause in severe consequences. Thus, a proper surface hardening of a ball stud component is imperative to prevent any problems during the service life of the component.

In this study, to improve the fatigue and wear resistance of a ball stud component, a surface hardening by induction heating method is applied. To investigate the effect of heat exposure time on the hardness profile of the ball stud, the ball studs have been heated for different heating times (2s, 3s, 4s, and 5s). After the induction hardening, hardness profiles and the microstructure of the specimens have been investigated. Additionally, the effect of various cooling times on the hardness profile of the ball studs and the effect of surface hardening on the resistance of the parts to the bending force has been examined.

2. Materials and method

In this study, 41Cr4 steel has been used to carry out the induction hardening process. 41Cr4 steel is an alloyed steel, which is generally preferred for components when high wear resistance and high hardness are required. The chemical composition of the 41Cr4 steel was obtained by a spectrometer device and has been shown in Table 1. The Chromium, Silicon and Manganese constituents in the chemical composition of the steel are known to provide better hardenability [22]. The mechanical properties of the steel were tested via a uniaxial tensile test, which was carried out according to the EN/ISO898 standards. The tensile stress-strain diagram of the 41Cr4 steel has been given in Figure 2., and its mechanical properties have been listed in Table 2.

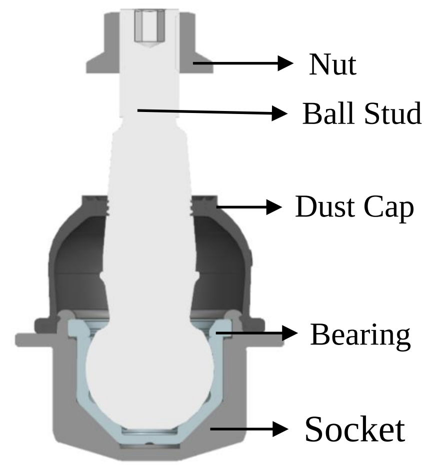

Figure 1. The section of a ball stud

Table 1. The chemical composition of the 41Cr4 steel

Material	Chemical composition (wt.%)	
41Cr4	C	0.406
	Cr	1.069
	Si	0.131
	Mn	0.660
	P	0.014
	S	0.004

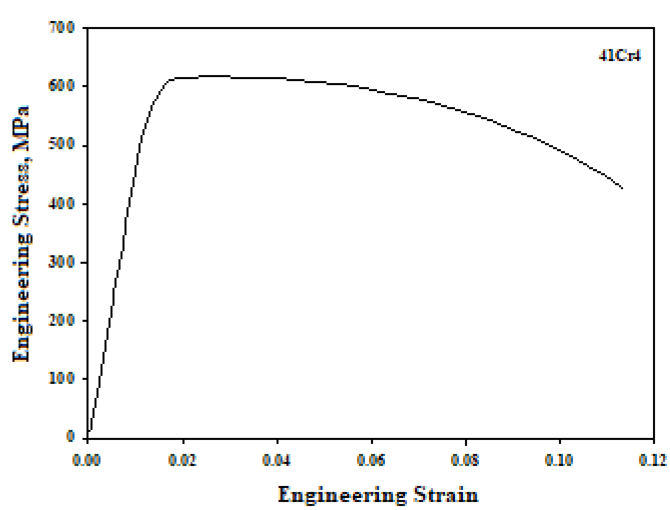

Figure 2. The Engineering stress-strain diagram of 41Cr4 steel

Table 2. The mechanical properties of 41Cr4 steel

Material	Mechanical Properties	
41Cr4	Yield Stress	592 MPa
	Tensile Stress	617 MPa
	Total Elongation	%11.2

The induction hardening of the ball studs has been carried out at constant frequency, 50 Hz, constant voltage, 338 V, and constant ampere, 135A. In Figure 3., the experimental test setup and its CAD view have been shown. In the experiments, the ball studs were rotated at 30 rpm during the induction heating process. In order to investigate the effect of heat exposure time, the specimens were heated for 2s, 3s, 4s and 5s. In preliminary tests, it was observed that heating the parts for more than 5 seconds led to an excessive hardening through the thickness of the ball stud parts. Hence, the heating time was limited to 5 seconds to control the hardness depth as well as the toughness of the parts. As soon as the heating cycle ended, water at 32 ℃ was sprayed over the specimen at 31 psi with a flow rate of 114 l/min to quench the specimens. After the hardening process was completed, the specimens were tempered at 170 ℃ temperature for 1 hour to remove the excessive brittleness of the specimens. The specimens were cut with wire – erosion method from half and the hardness levels of the specimens from the outer surface to the inner region were measured with 0.2 mm steps by using a Vickers microhardness measurement device. In the Vickers microhardness tests, the specimens were indented with a 300g load for 10s dwell time. To observe the microstructure, the specimens were ground with 240, 400, 600, 800, 1000 and 1200 grit paper and polished with 3 and 1 micron diamond suspension. Polished specimens were then etched with 2% Nital solution to observe the microstructure. Additionally, bending experiments were carried out on the hardened ball stud specimens. In the bending experiments, the specimens were horizontally fixed, and 2 mm vertical displacement was applied from a distance of d = 25 mm via a circular rod as shown in Figure 4. Finally, to observe the effect of cooling time on the hardness behaviour of the ball stud specimens, the induction heated samples for 3s were cooled for different durations of times (3s, 5s and 7s).

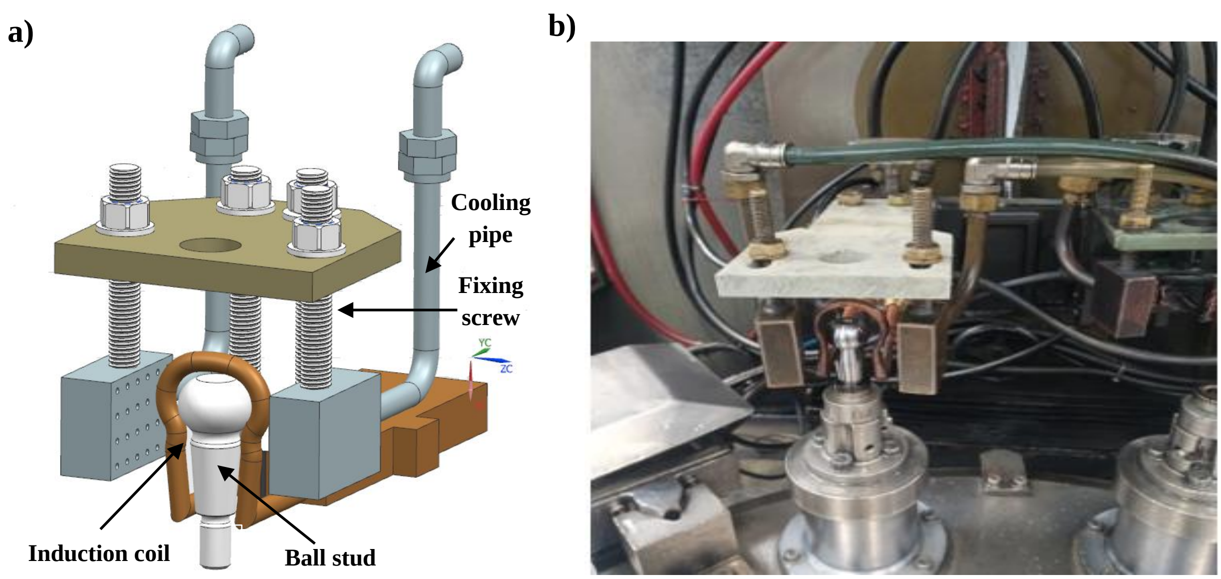

Figure 3. a) CAD view of the experimental setup, b) experimental setup of induction hardening process

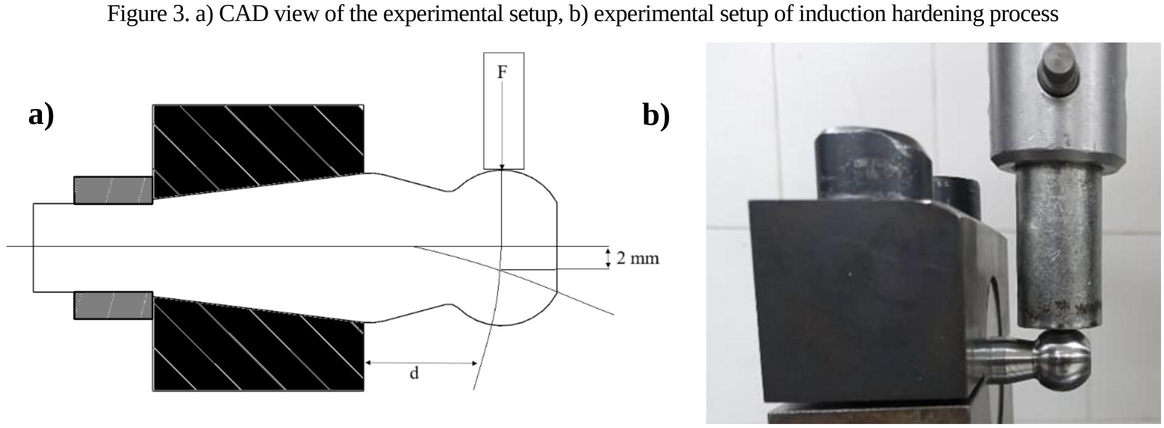

Figure 4. a) Schematic view of the bending experiment and b) the experimental setup for the bending experiments

3. Results and discussions

The surface hardening process by induction heating is achieved by heating the specimens quickly and then rapidly cooling. The hardness values of the ball stud specimens which are induction heated for different durations of time have been shown in Figure 5. It can be seen that heating the specimens for longer durations of time has led to a considerable rise in the hardness values observed at the outmost edges, and through the thickness as well. However, it is also visible that the heating of the specimens for only 2s has not caused any hardness increase at the outer edge, which suggests that the specimen temperature has not reached the austenitization temperature level necessary for the martensite transformation.

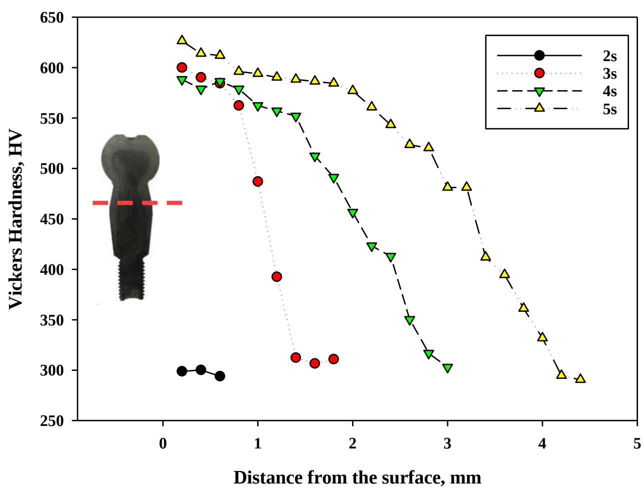

Figure 5. The hardness values of the ball stud specimens induction heated for different durations of time

The increase in the hardness levels of the specimens as compared to the base material has been 2.5% for 2s, 106% for 3s, 102% for 4s and 115% for 5s. It is seen that a significant improvement in the hardness level of the ball stud specimen could have been obtained after induction heating the specimens for 3s and more. The similar hardness levels obtained at the outer edge of the specimens when heated for 3s and 4s suggest that the temperature level of the ball stud specimen has not changed significantly or that the rise of temperature level with the increase of heating time from 3s to 4s has not been so significant that it caused a considerable change in the hardness value at the outmost region of the part. However, the hardness level of the specimen in the interior regions has kept being higher when it is heated for 4s as compared to heating for 3s. The increase in heating time during induction hardening has caused the temperature level of the specimen to rise and also let the high temperature penetrate deeper into its center. Hence, the depth of the hardness zone has increased with the increase in heating time. The microstructure of the 41Cr4 steel after induction hardening and tempering has been shown in Figure 6. The white areas in the microstructures represent the martensitic structure, while the dark areas represent the ferrite-pearlite structures. It can be seen that the outer regions of the 41Cr4 steel have transformed to martensitic structures in the hardened zone, while ferrite-pearlite and martensitic structures have been observed to coexist in the transition zone. However, no martensitic transformation has been seen in the base material of the specimens.

Figure 6. The microstructure of the hardened ball stud specimen. (Heating time: 3s)

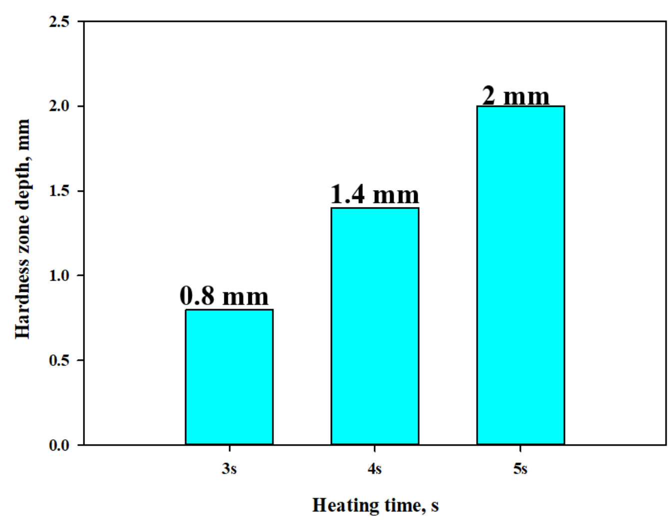

Figure 7. The hardness zone depth of the ball stud specimens induction heated for different durations of time

The hardness depth of the induction-hardened specimens has been shown in Figure 7. Since the specimen heated for only 2s has not shown any hardening due to insufficient heating time, its hardness depth has been omitted in Figure 7. When the induction heating time is increased to 4s and 5s, the hardness zone depth of the ball stud specimen has increased by 75% and 150%, respectively as compared to the heating the specimens for 3s.

The hardened specimens induction heated for 2s, 3s, 4s and 5s and also their microstructures showing the hardness zone (HZ), transition zone (TZ) and the base material (BM) have been shown in Figure 8. Due to insufficient hardening for 2s heating, the HZ and the TZ couldn't have been observed. The increase in the hardness zone depth of the specimens is also visible by the deeper penetration of the light grey area as the heating time is increased as shown in Figure 8. It is seen that the induction heating time has a direct impact on the hardness level and the hardness depth of the specimens. Similarly, in a study conducted by Shtarbakov et al. [14], the researchers have also shown that the heat exposure time has an improvement effect on the hardness layer and the hardness of the specimens.

During the service life of a ball stud part, it can sustain many different and repetitive forces including bending forces. In order to observe the effect of heating time during induction hardening on the resistance of the ball stud to the bending, the hardened specimens have been tested in bending experiments and the results have been shown in Figure 9. It can be seen that the increase in heating time has considerably improved the bending resistance of the ball stud specimens. The bending resistance of the specimens has improved by 4.05%, 4.40% and 7.41% by heating the specimens for 3s, 4s and 5s, respectively, in comparison to heating for 2s. As expected, the resistance of the specimens to the bending when heated for 3s and 4s has been quite similar due to the similar hardness levels obtained at these heating durations as shown in Figure 7. Finally, in addition to the effect of heating time during induction hardening, the effect of cooling duration on the hardness level of the specimens has been investigated and the results have been shown in Figure 10. However, it can be seen that the variation of cooling time has not caused a noticeable change in the hardness behaviour of the ball stud specimen. It can be thought that the cooling of the ball stud specimens above 3s is not necessary.

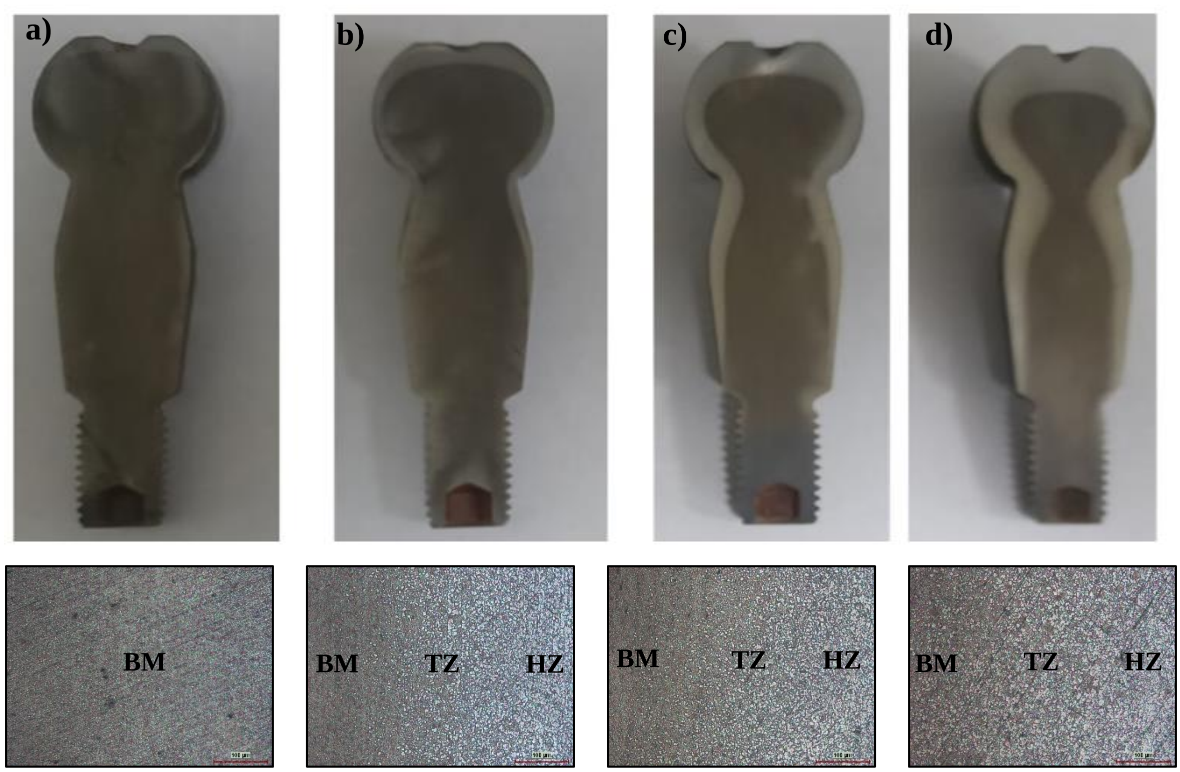

Figure 8. The induction hardened specimens heated for **a)** 2s, **b)** 3s, **c)** 4s and **d)** 5s

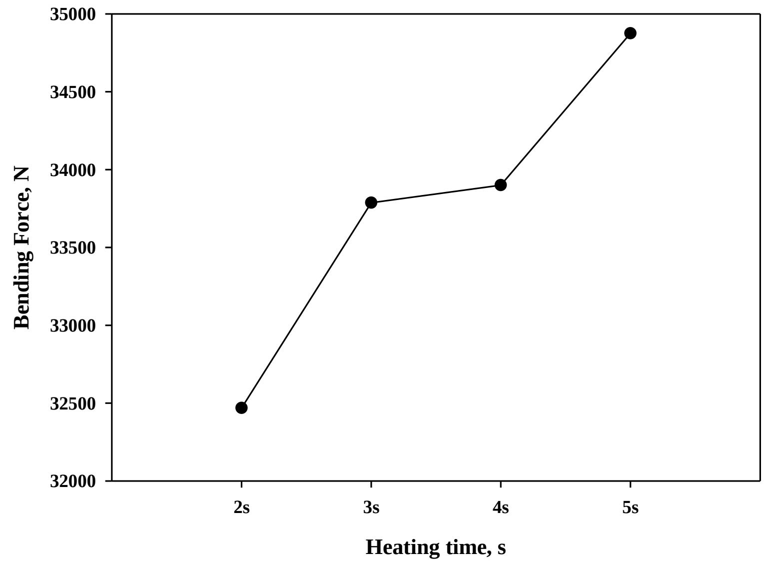

Figure 9. The resistance of the hardened specimens induction heated for 2s, 3s, 4s and 5s

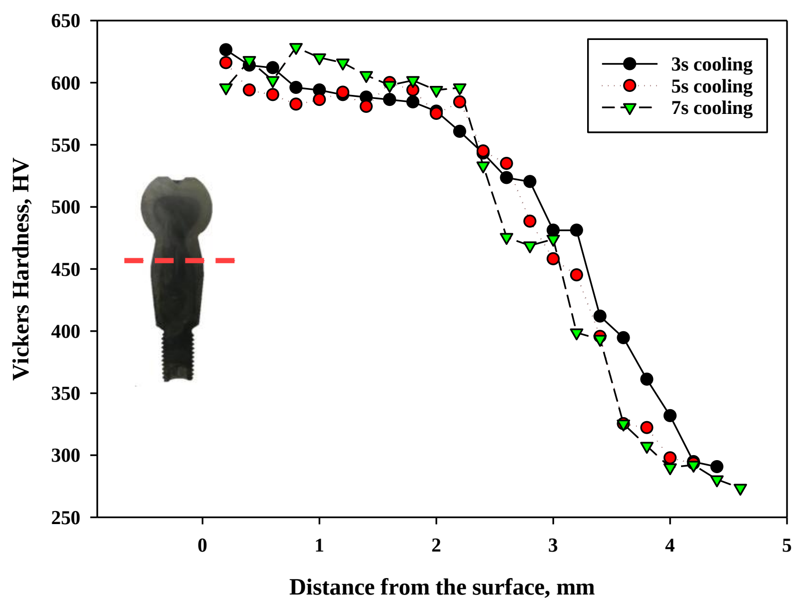

Figure 10. The hardness values of the ball stud specimens induction heated for 3s and cooled for 3s, 5s and 7s.

4. Conclusions

In this study, induction hardening of ball stud parts made of 41Cr4 steel has been carried out under different heating and cooling times to observe their impact on the hardness profile. Additionally, the effect of induction hardening on the bending resistance of the ball stud specimens has been investigated. The main conclusions drawn from the study have been listed below:

- The increase in heating time has a direct effect on improving the hardness values of the specimens. The hardness levels of the induction-hardened specimens through heating for 2s, 3s, 4s and 5s have improved by 2.5%, 106%, 102% and 115% as compared to the hardness level of the base material, respectively. It has been thought that the increase in heating time has led to higher temperatures in the specimen, thus, improving the hardness level
- The increase in heating time has also led the high temperature to penetrate deeper into the interior regions of the ball stud specimens and provided a larger layer of hardness zone. The thickness of the induction hardened zone has been obtained to be 0.8 mm for 3s, 1.4 mm for 4s, and 2 mm for 5s.

- The resistance of the ball stud specimens to the bending have considerably improved by the induction hardening. The increase in heating time has led to the increase in the resistance of the ball stud specimens to the bending force.
- The cooling of the ball stud specimens for 3s, 5s and 7s has not caused a distinct difference in the hardness profile. It is thought that the cooling of the specimens for at least 3s has been sufficient enough to provide the martensitic transformation.

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Conflict of Interest Statement

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

CRediT Author Statement

Fatih Helimergin: Data curation and Experimental tests
Toglahan Civek: Writing - original draft and Validation
Nuri Şen: Conceptualization, Supervision and Validation

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