DOI 10.36146/2025_0708_48

Effect of initial metallurgical conditions on induction hardening process on UNI EN 42CrMo4 shafts

E. Bertarelli, M. Cassola, A. Fortini, M. Merlin

In industrial practice, heat treatment companies are usually required to perform induction hardening on parts with different metallurgical supply conditions resulting from different heat treatment routes previously applied. As a result, understanding the effect of material supply conditions on the induction hardening process parameters is of great interest for heat treatment companies. This knowledge enables the proper adjustment of process parameters, ensuring optimal outcomes and consistency across diverse material conditions.
In this study, shafts manufactured in UNI EN 42CrMo4 steel were subjected to induction hardening treatment starting from different supply conditions. The study focuses on two distinct case studies: • Case study 1 investigates the influence of different preliminary heat treatment routes (normalizing, quenching and tempering); • Case study 2 explores the effect of repeated induction hardening, namely the hardening on a part that has been already hardened previously.

KEYWORDS: INDUCTION HARDENING, SUPPLY CONDITIONS, MICROSTRUCTURE, HARDNESS;

INTRODUCTION

Induction hardening is currently used to increase the performance of a wide variety of mechanical components, including axles, shafts, and gears, for several applications, especially in vehicles in the automotive field. It is a reliable and time-saving process that can be used to selectively harden portions of the above-mentioned parts to improve strength, hardness, wear resistance, and fatigue behavior [1]. In contrast to case hardening and nitriding, induction hardening does not require heating the whole part and allows the hardening of the material only where needed. The optimization of the process parameters is fundamental for achieving the desired surface mechanical properties. The design of the inductor, its geometry, and the selection of the induction heating frequency are crucial to precisely control the localized heating of the material; the temperature distribution during heating must be as uniform as possible and achieved in the shortest time to maximize the efficacy of the process [2]. The metallurgical changes should occur only within the established thickness, minimizing the heating effects on adjacent areas to preserve the component's overall integrity [3]. Induction hardening consists of three different steps, i.e. austenitization, quenching and tempering, but the metallurgical supply conditions of the materials can affect the final properties of the hardened surface. The

E. Bertarelli, M. Cassola
TIMAF S.n.c., via Ciauri 15, 29121 Piacenza (Italy)

A. Fortini, M. Merlin
Department of Engineering (DE) – University of Ferrara, via Saragat 1, 44122 Ferrara (Italy)

literature highlights that bulk pre-heat treatments, such as normalizing, quenching and tempering, play a critical role in determining the outcome of the process [3,4]. In this paper, two case studies typical of industrial practices are collected to point out that not only the nominal chemical composition of the steel but also the supply conditions are essential factors to be considered to guarantee the expected microstructure and mechanical properties.

MATERIALS AND METHODS

Two different case studies were investigated in this industrial research, detailed as follows. All heat treatments were performed at TIMAF S.n.c. heat treatment factory. Chemical analysis hardness testing and Optical Microscopy (OM) inspections were conducted at TIMAF S.n.c. Metallurgical Laboratory, while further microscope analyses with a Scanning Electron Microscope (SEM) were executed at the Department of Engineering (DE) of the University of Ferrara. A Nikon Eclipse LV150N (Nikon Corp., Tokyo, Japan) was used for OM analyses, whereas a Zeiss EVO MA15 (Carl Zeiss, Jena, Germany) scanning electron microscope was adopted for SEM investigations. The shafts were all induction-hardened on a SAET 3MBE induction hardening machine with a vertical setup. During the process, the part rotates around its axis while a ring inductor translates in the axial direction with a supply current frequency f equal to 15 kHz. A polymer-based quenching solution is used for quenching.

At TIMAF S.n.c., chemical composition was determined by a GNR S7 Metal Lab Plus Optical Emission Spectrometer (OES). Samples were ground and polished according to the standard metallographic preparation procedures. Rockwell hardness was measured by a Future-Tech LC-200RB hardness tester (Future-Tech Corp., Kawasaki, Japan) according to the UNI EN ISO 6508-1 standard [5]. Vickers hardness (HV10, HV1, HV0.1) and hardness profiles were recorded by an OMAG WIKI200JS microhardness tester (OMAG, Induno Olona, Italy), according to UNI EN ISO 6507-1 [6] and UNI 11153-3 [7] standards.

First case study: hollow shafts with various supply conditions

Three hollow shafts made of 42CrMo4 steel, according to the UNI EN ISO 683-2:2018 standard, with an outer diameter of 40 mm and an inner diameter of 15 mm, were used for this case study. The chemical composition is detailed in Tab.1.

Tab.1 - Measured chemical composition (wt. %) of the 42CrMo4 steel. Mean values (5 measurements).

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Fe
0.424	0,221	0.759	0.010	0.029	1.039	0.182	0.112	0.027	0.183	Bal.

All shafts were normalized at 870 °C for 2 hours (hereinafter referred to as +N), whereas only two of them were subsequently austenitized at 860 °C for 2 hours, oil quenched, and respectively tempered at 400 °C (hereinafter referred to as +QT(400)) and 600 °C (hereinafter referred to as +QT(600)) for 2 hours.

After the heat treatments, the shafts were all induction-hardened at the TIMAF S.n.c. plant on an induction hardening machine with a vertical setup. In this case, the induction hardening process was set up to guarantee, according to the final Customer's request, an effective hardening depth of Tps20 with a surface hardness class of 58 HRC according to UNI 10932:2001 standard [8]. This means that an effective hardening depth of 2 mm with a tolerance of +1,5 mm, a surface hardness in the range of 58 - 62 HRC and a limit hardness of 523 HV1 was the target. Finally, from each shaft, three transversal sections were cut to obtain three annular samples of 10 mm in thickness; one of the three samples was maintained in the induction-hardened condition, while the others were tempered at 140 °C for 2 hours (T140) and 170 °C for 2 hours (T170), respectively.

Second case study: shafts undergoing repeated hardening

Two shafts in 42CrMo4 steel, according to the UNI EN ISO 683-2:2018 standard, with an outer diameter of 73,5 mm, were used for this case study. The chemical composition is detailed in Tab. 2.

Tab.2 - Measured chemical composition (wt. %) of the 42CrMo4 steel. Mean values (5 measurements).

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Fe
0,399	0,229	0,816	0,006	0,024	1,075	0,170	0,096	0,022	0,119	Bal.

Shafts were provided in quenched and tempered conditions by the Customer. The induction-hardening process was set up to guarantee, according to the final Customer's request, an effective hardening depth of Tps30 with a surface hardness class of 58 HRC according to UNI 10932:2001 standard [8]. This means that an effective hardening depth of 3 mm with a tolerance of +2 mm, a surface hardness in the range of 58 - 62 HRC and a limit hardness of 523 HV1 was the target.
The first shaft was induction hardened one time. The second shaft was induction hardened three times in sequence, with a holding time of 5 minutes, with the water cooling system activated to have near zero residual heat in the part before executing the following hardening cycle. Both shafts were finally tempered at 170 °C for 2 hours.

RESULTS AND DISCUSSION

First case study: hollow shafts with various supply conditions

In Tab. 3, all hardness and microhardness data acquired at the surface and the bulk of the steel before and after being induction-hardened and/or tempered at 140 °C and 170 °C are collected. Before induction hardening, the steel in the normalized condition shows the lowest surface hardness (31 HRC), even if the bulk hardness (350 HV10) is higher than that after quenching and tempering at 600 °C (315 HV10). Each heat-treated condition shows the conventional trend of decreasing surface hardness versus tempering temperature.
Figure 1 summarizes the obtained hardening depth for the different process routes. The reported differences in terms of effective hardening depth are not significant for generic industrial applications: when specific loads are not critical, the mechanical part performances are expected to be comparable for the different cases. This finding confirms that induction hardening effectively "overwrite" both +N or +QT metallurgical conditions.
As expected, +QT(400) and +QT(600) samples show different base material hardness: this results in different hardness profile trends in the transition zone and thus in a shift of approximately 0.3 mm in effective hardening depth. The +N samples are aligned in terms of effective hardening depth to +QT(600) samples. It is worth to note that tempering up to 170 °C does not significantly impact the hardening depth. However, +N shows variations of measured hardening depth after tempering, while a strong trend is not found for +QT.
As reviewed in literature [9], +QT prior structure is the most favorable, ensuring rapid transformation, with a fast and consistent response of the steel to induction hardening, minimum grain growth and shape/size distortion. Potentially, this condition can lead to higher hardness and higher effective depth. If the initial microstructure has a significant amount of coarse pearlite and, most importantly, coarse ferrites or clusters or bands of ferrites, then the structure is not considered favorable. After quenching, a mixed ferritic-martensitic microstructure can form. In the present +N case study however, the prior microstructure is not characterized by coarse-grained ferrite or pearlite and this is demonstrated to allow the induction hardening process to successfully occur, similarly to the +QT case.
But, as mentioned in [9], the local required induction hardening temperature depends on the material's prior microstructure: higher temperatures are required to achieve homogeneous austenite (in terms of carbon homogeneity) in +N rather than +QT conditions. Focusing on the transition zone, where the transformation is obtained by thermal diffusion, we believe this effect is emphasized. Hence, in the +N metallurgical condition, after quenching the martensite structure could be not fully uniform: tempering is then driving additional transformations at different temperatures, resulting in variations of detected hardening effective depth.

Tab.3 - Hardness data (HRC: mean of n. 5 measurements; HV10: mean of n. 5 measurements; HV1: mean of n. 20 measurements).

HEAT-TREATED CONDITION	BULK HARDNESS (mean values)	INITIAL SURFACE HARDNESS (mean values)	PROCESS ROUTE	SURFACE HARDNESS AFTER INDUCTION HARDENING	
Normalized	350 HV10	31 HRC	+N	63 HRC	722 HV1
			+N +T140	59 HRC	710 HV1
			+N +T170	57 HRC	673 HV1
Quenched and tempered at 400 °C	480 HV10	45 HRC	+QT(400)	60 HRC	696 HV1
			+QT(400) +T140	59 HRC	690 HV1
			+QT(400) +T170	57 HRC	663 HV1
Quenched and tempered at 600 °C	315 HV10	33 HRC	+QT(600)	61 HRC	715 HV1
			+QT(600) +T170	60 HRC	704 HV1
			+QT(600) +T170	58 HRC	667 HV1

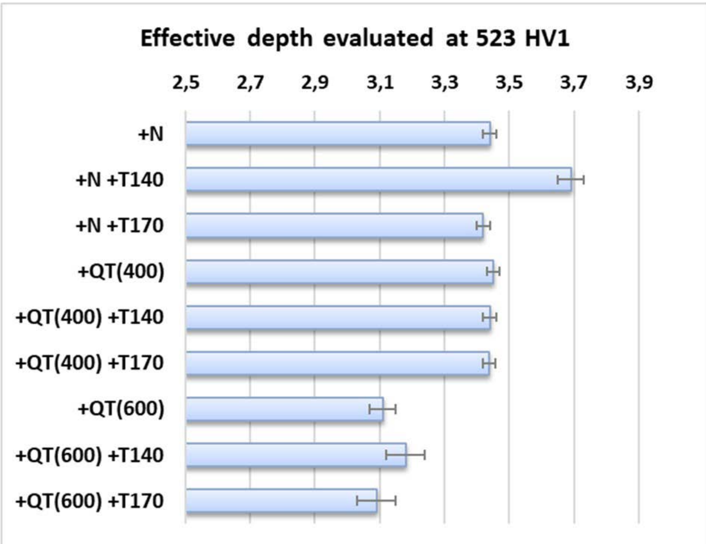


Fig.1 - Effective hardening depth for the studied process routes (mean of n. 3 microhardness profiles).

Fig. 2 summarizes the SEM micrographs of the steel in the +N and +QT(600) conditions after the induction hardening treatment by comparing the bulk and induction-hardened zones. From the low-magnification SEM micrographs (Fig. 2a and 2d), the effects of the different supply conditions could be observed. As for the +N condition, in the bulk region (Fig. 2c), the microstructural constituents were identified as ferrite and perlite, with a slightly higher amount of ferrite than that of perlite due to air cooling during normalizing: the appearance of perlite is quite like upper bainite due to the hardenability the 42CrMo4 steel. This microstructure is compatible with the good hardenability of the investigated steel in the +N condition and justifies the initial high values of hardness in the normalized condition (see Tab. 2). By contrast, in the induction-hardened region (Fig. 2b), the microstructure is very fine and identified as high tetragonal martensite.

Concerning the +QT(600) condition, the microstructure in the bulk zone (Fig. 2f) can be ascribed to tempered martensite; in the induction-hardened region (Fig. 2e), the martensitic phase becomes finer than in the bulk region.

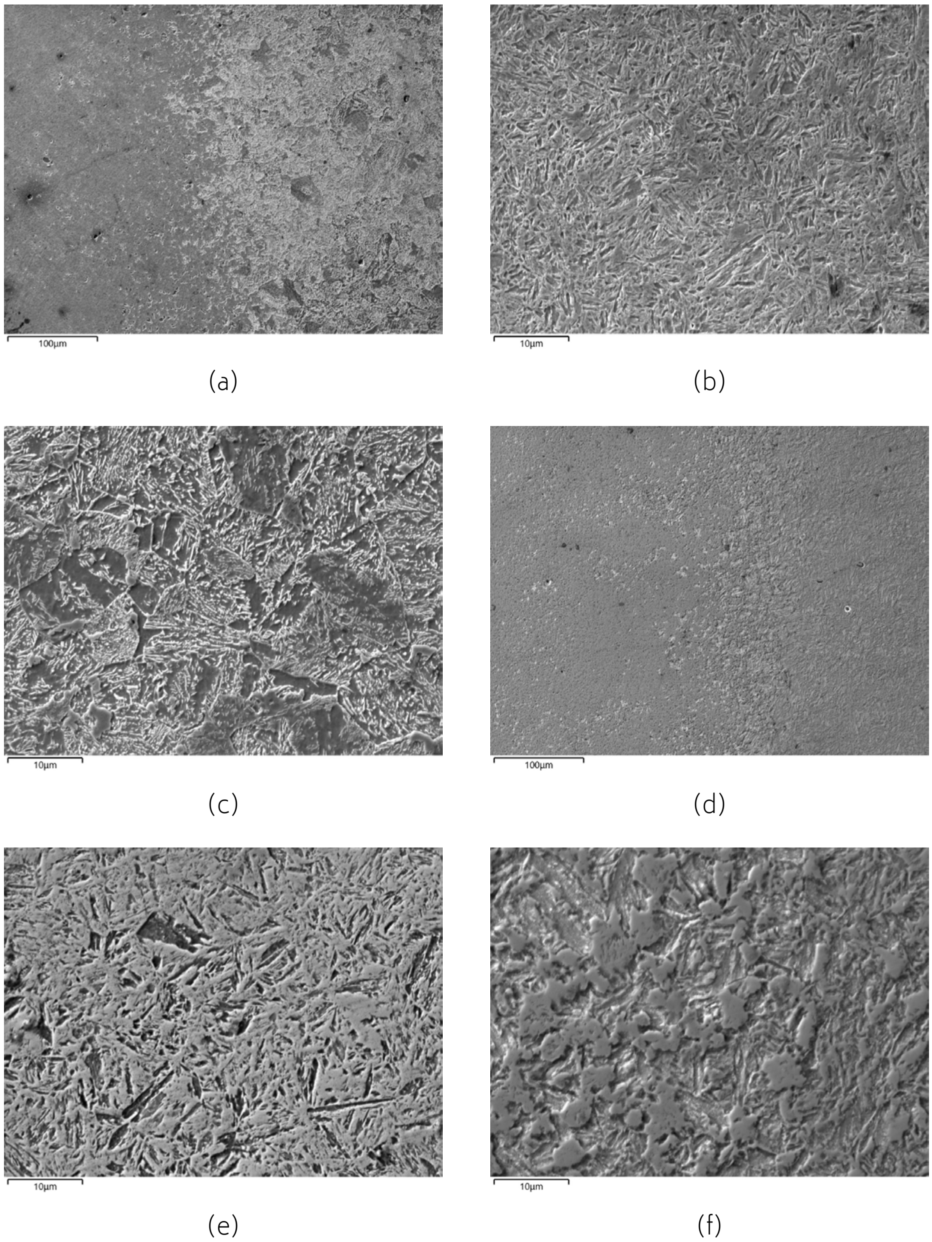


Fig.2 - SEM micrographs: a) +N, low magnification micrograph of the transition region; b) + N, induction-hardened region; c) +N, bulk region; d) +QT(600), low magnification micrograph of the transition region; e) +QT(600), induction-hardened region and f) +QT(600), bulk region.

To study the hardness transition zone, namely the hardness drop in the limit zone between the induction-hardened region and the base material, hardness profiles were performed on the cross sections of the +N and +QT(600) samples across the transition zone. The results are reported in Fig. 3 and they show a steeper decrease in hardness in the transition zone in the +N condition (Fig. 3a) with respect to that of the +QT(600) condition (Fig. 3b). This agrees with the different effects caused in the microstructure in the transition zone by the induction hardening process.

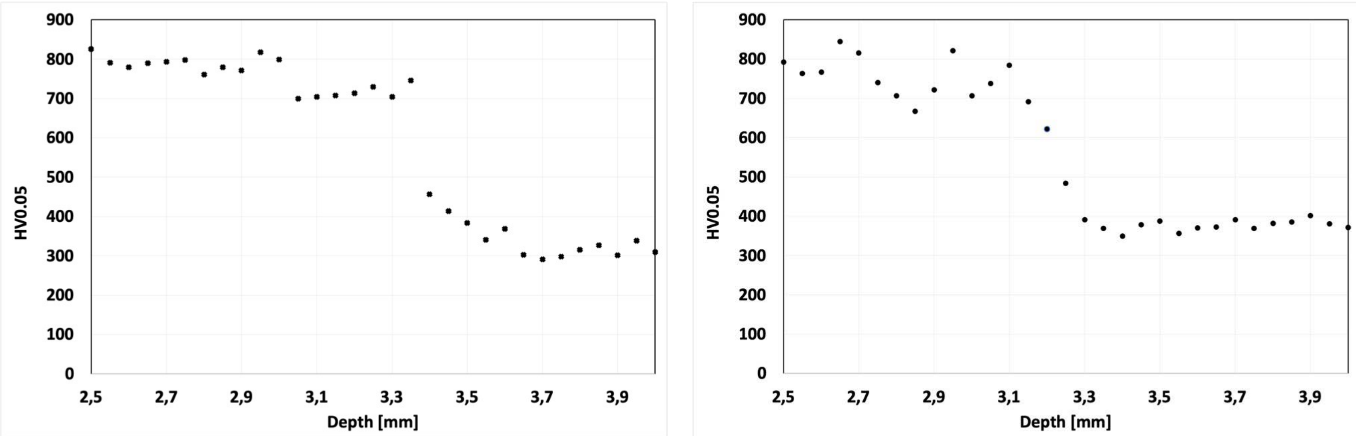


Fig.3 - Microhardness HV0.05 profiles in the transition zone: a) +N; b) +QT(600).

Second case study: shafts undergoing repeated hardening

Hardness and microhardness tests were performed on the surface and the cross-section of the analyzed samples and data are collected in Tab. 4. From a general standpoint, no significant variations can be highlighted in terms of surface hardness and effective hardening depth when comparing a single induction hardening cycle, i.e. one repeat, with three sequential hardening cycles, i.e. three repeats. This finding matches the empirical rule that subsequent induction hardening overrides the previous process if similar parameters are applied.

Tab.4 - Hardness data (HRC: mean of n. 5 measurements; HV10: mean of n. 5 measurements; HV1: mean of n. 20 measurements).

HEAT-TREATED CONDITION	BULK HARDNESS (mean values)	INITIAL SURFACE HARDNESS (mean values)	PROCESS ROUTE	SURFACE HARDNESS AFTER INDUCTION HARDENING	
1 repeat	290 HV10	29 HRC	4,10 mm	58 HRC	675 HV1
3 repeats			4,05 mm	58 HRC	687 HV1

The analysis of the hardness profiles (Fig. 4) points out that, while comparable microhardness is detected on the hardened zone, a difference is kept in light of the transition zone. The OM inspection reported in Fig. 5 confirms that repeated execution of the induction hardening process leads to the creation of an extended interface zone between the base material and fully transformed (martensitic) material. The higher thickness of the transition zone in the one repeat condition (Fig. 6a) than that in the three repeats condition can also be observed by the SEM micrographs. By comparing the micrographs reported in Fig. 6c and Fig. 6f, which refer to the induction-hardened zones of the two different conditions, just a slight increase in size of the platelet-like martensitic microstructure can be detected after three sequential hardening cycles; nevertheless, no significant variations in the hardness were detected (Fig. 4a). No thermal effects were induced to the quenched and tempered microstructure in the bulk zone (Fig. 6h).

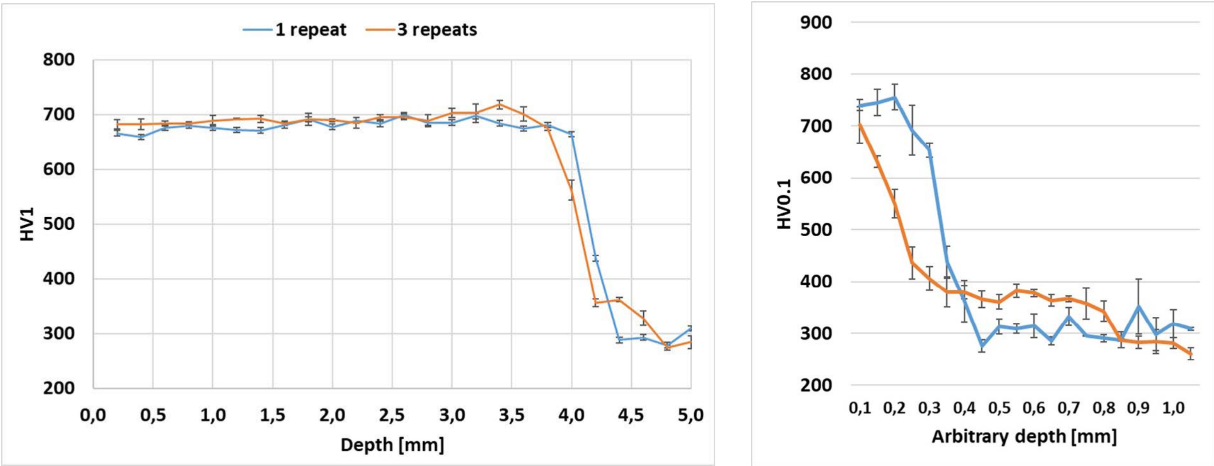
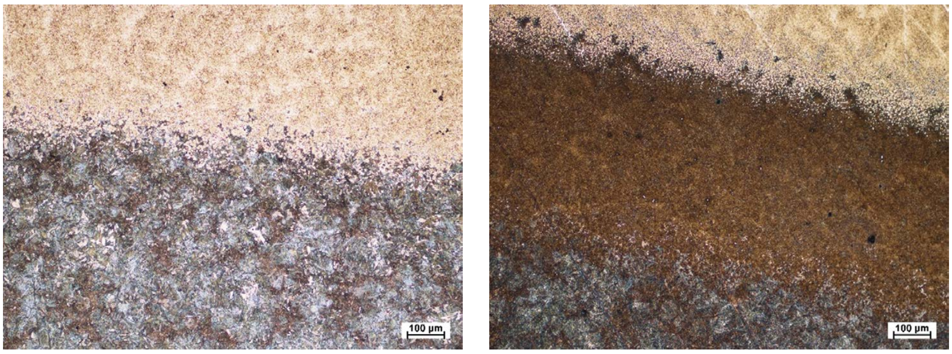
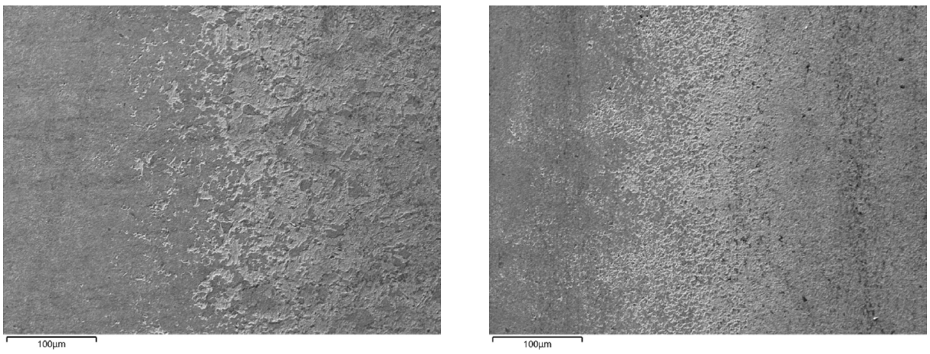


Fig.4 - (a) Microhardness HV1 profiles after induction hardening (AVE and SD on 3 profiles).
(b) Microhardness HV0.1 profiles, detail on hardness transition zone (AVE and SD on 5 profiles).

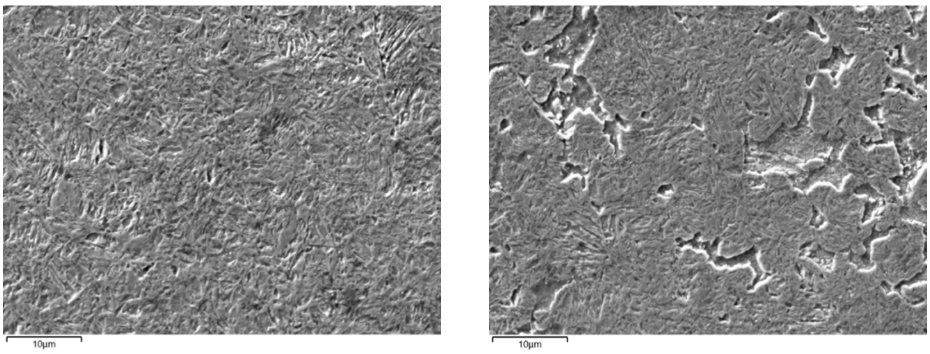


(a) (b)

Fig.5 - OM micrographs of transition zone: a) 1 induction hardening cycle; b) 3 induction hardening cycles.



(a) (b)



(c) (d)

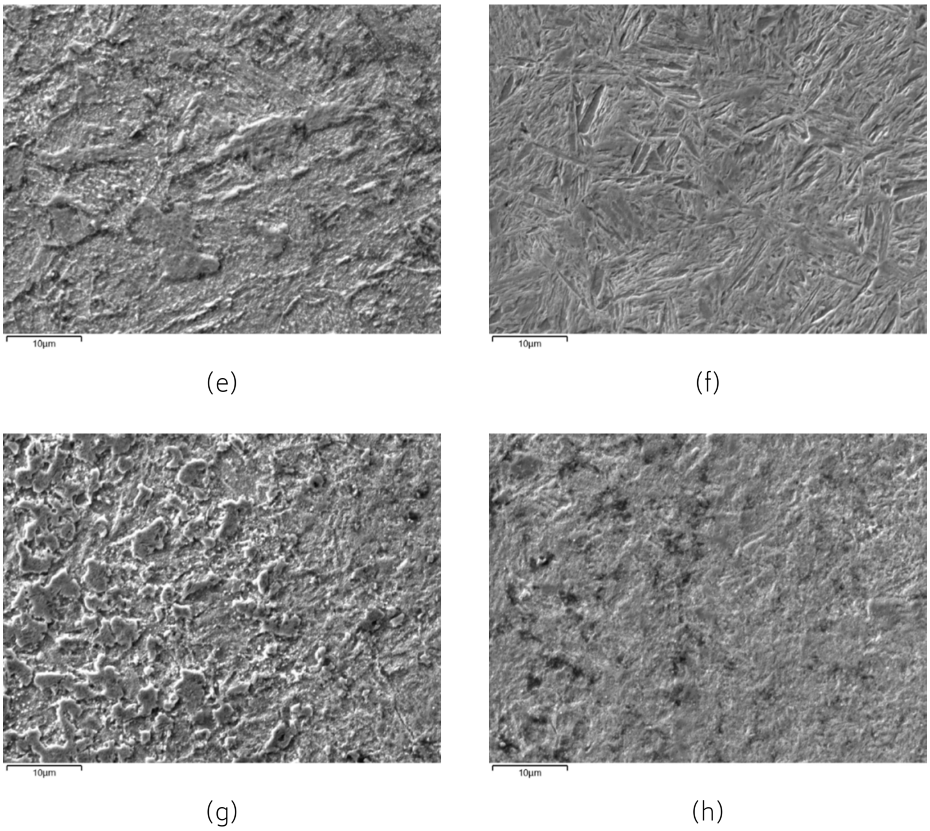


Fig.6 - SEM micrographs: a) and b) low magnification micrograph of the transition region for 1 and 3 induction hardening repeats, respectively; c), d), e) induction-hardened, transition and bulk regions for 1 repeat; f), g), h) induction-hardened, transition and bulk regions for 3 repeats.

CONCLUSIONS

In this work, two case studies were deeply investigated to point out how several key factors can impact the microstructure and the mechanical properties of induction-hardened steel parts in industrial practice. Apart from the induction hardening parameters related to the induction hardening machine setup (inductor geometry, current frequency, translation inductor speed, quenching phase, etc.), the results show that the metallurgical supply condition of steel and/or the prior applied heat treatments play a role in the determination of the final microstructure and thus the mechanical properties.

Case study n. 1 showed that, after induction hardening, surface hardness and effective hardening depth in a UNI EN 42CrMo4 steel are slightly influenced by the initial metallurgical supply condition, either normalized or quenched and tempered. By analyzing microhardness data, supported by microstructure investigations, it was found that both the microstructure and the local mechanical properties in the transition zone differ in the different considered sample conditions. This could potentially impact the mechanical performances of the part under severe loading conditions, requiring dedicated investigations and potentially mechanical testing of parts, to achieve a suitable process optimization. Nevertheless, based on the TIMAF S.n.c. experience gained after extensive interaction with Customers, when applications are not critical and specific loads are not so high, no issues are expected.

Case study n. 2 showed that no significant change in hardness and effective hardening depth is achieved when the induction hardening is repeated up to 3 times in the same location. Micrographic inspection and low-load hardness measurements reveal that the transition zone between the hard layer and base material is strongly impacted by the repeated induction hardening process.

REFERENCES

[1] V. Rudnev. Induction Hardening of Gears and Critical Components. Gear Technology. September/October 2008, 58-63.
[2] M. Horynová, M. Juliš, L. Cˇelko, J. Švejcar. Failure analysis of induction hardened injector body. Engineering Failure Analysis, 56, 2015, 538-544.
[3] V.I. Rudnev, D. Loveless, R. Cook, M. Black. Induction Hardening of Gears: A Review. Heat Treatment of Metals, 2003, 4, 97-103.
[4] C. Rathinasuriyan, K. Karthik, S. Udhayaraj, Sunil Bishwakarma. Investigation of induction hardening on heat-treated EN8 steel by alternately timed quenching process. Materials Today: proceedings (article in press).
[5] UNI EN ISO 6508-1:2023 – Materiali metallici - Prova di durezza Rockwell - Parte 1: Metodo di prova – Metallic materials - Rockwell hardness test - Part 1: test method.
[6] UNI EN ISO 6507-1:2023 – Materiali metallici - Prova di durezza Vickers - Parte 1: Metodo di prova – Metallic materials - Vickers hardness test - Part 1: test method.
[7] UNI 11153-3:2006 – Misurazione dello spessore di strati superficiali induriti su elementi di lega ferrosa - Tempra superficiale.
[8] UNI 10932:2001 – Trattamenti termici dei materiali metallici Tempra superficiale dei materiali ferrosi.
[9] V.I. Rudnev, D. Loveless. 12.15 - Induction Hardening: Technology, Process Design, and Computer Modeling. Comprehensive Materials Processing, 2014, 489-580.

TORNA ALL'INDICE >