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Induction hardening of steels with use of the device for incremental forming of round bars HDQT-R 30-12

M Peković, J Vrtáček, T Janda, J Volkmannová

Faculty of Mechanical Engineering – Regional Technological Institute, University of West Bohemia, Univerzitní 8, 306 14 Pilsen, Czech Republic

E-mail: pekovicm@rti.zcu.cz, vrtacekj@rti.zcu.cz, jandat@rti.zcu.cz, volkmann@rti.zcu.cz

Abstract: Induction hardening is mainly used for treating parts in which high hardness, wear-resistance, and ductile core are required, such as spur gears, wind turbine rings, and bearings. Innovative induction hardening processes are also developed for complex automotive components, such as camshafts and crankshafts. In the process, steel is heated by passing high-frequency alternating current through a coil which is equivalent to the primary winding of a transformer. The material to be heat-treated is equivalent to a short-circuited secondary winding. The HDQT-R 30-12 device for incremental forming of round bars includes modules which can be used for heat-treating bars after rolling or even without rolling. Heating is provided by five induction coils at a faster rate than in a chamber furnace. In addition, there is less oxidation of the material surface. This paper presents findings related to microstructures and hardnesses in 42CrMo4, 13CrMo4, and S235JR steel grades after heating at different inductor coil power settings with subsequent hardening in a water bath.

Keywords: induction hardening, quenching, AHSS, hardness

1 Introduction

The increasingly stringent requirements for mechanical properties of steels and the pressure on prices of final products lead to improvements in production processes. Induction hardening belongs to treatment methods which are widely used today. Electromagnetic induction was discovered by Michael Faraday in mid-1800s. The first use of induction heating for melting metals dates back to 1916. Induction heat treatment began to be used in the 1930s, mostly for induction hardening of pegs and crankshafts [1]. Today, induction hardening is important to the manufacture of gears, bearings, camshafts and crankshafts. In these applications, high hardness and wear resistance are sought, along with a good toughness in the core of the part [2]. Improved surface properties lead to longer life of treated products of this kind. Generally-recognized benefits of induction heat treatment include fast heating rates, high energy efficiency, rapid initiation and deactivation, environmental friendliness and a negligible extent decarburization of the part's surface. Induction hardening consists of two steps: induction heating and quenching with an appropriate quenchant [3].

Quenching belongs to heat treatment processes which are accompanied by phase transformations in steel. Typical quenching temperatures are higher than A_{c3}, which means quenching from the fully-austenitic region. Generally, the purpose of quenching operations is to produce martensitic structures. Formation of martensite depends on several factors. The first one is the critical cooling rate which must be attained if martensite is to form. The amount of carbon is another factor. With increasing carbon content, hardness of quenched steel increases [4].

Induction heating finds use in experimental forming processes where rapid heating to forming temperatures is needed. For the same purpose, this investigation was carried out on equipment for developing incremental forming processes which has induction heating capability.

2 Experimental programme

The HDQT – R 30 – 12 equipment for developing incremental forming processes (**H**igh **D**eformation **Q**uenching and **T**empering) is primarily intended for reducing the diameter of round bars. Its modular design makes it suitable for post-rolling heat treatment and heat treatment both with and without reducing the diameter. Available operations include induction hardening with quenching in water bath. The equipment features five induction coils in the front part of the rolling mill, upstream of the rolling stands, and a quenching bath in the rear part of the rolling mill (Figure 1) [5].

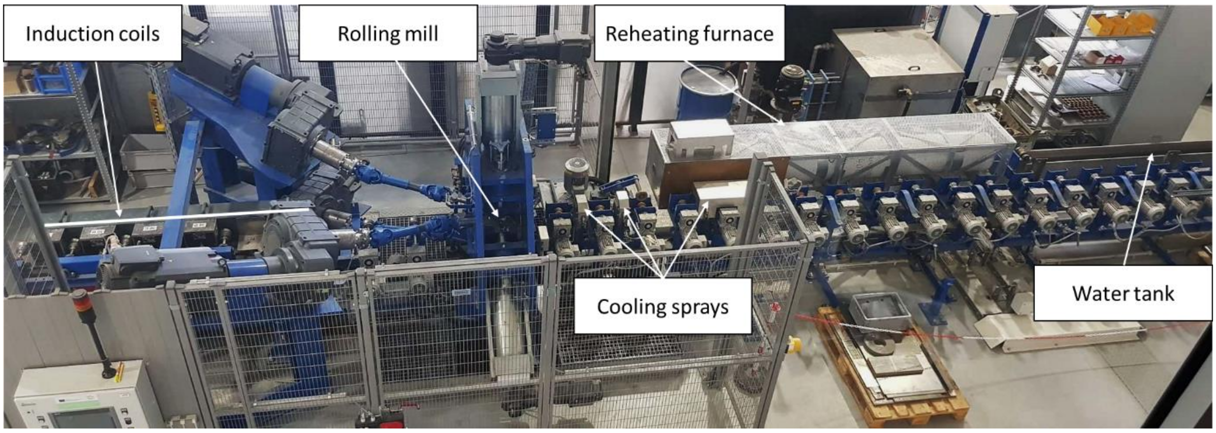

Figure 1. Device for incremental forming HDQT-R 30-12.

Induction coils are split between two circuits, where each has its own power supply. The first circuit comprises four heating coils with a power of 200 kW. The other includes a single 50 kW coil which reheats the bar to the desired forming or heat treatment temperature [6].

This experimental programme was concerned with induction hardening. The purpose was to find and test an appropriate power configuration for the induction coils to reach the desired optimum temperature for full austenitization of the materials under investigation and observe the effects of chemical composition of steel on its ability to be heated by induction coils. Three steel grades of different compositions were chosen for the experiments (Table 1).

Table 1. Chemical compositions of steels under investigation.

Material	C	Si	Mn	Cr	Mo	S	P	A_{c1} [°C]	A_{c3} [°C]
42CrMo4	0.44	0.3	0.8	1.2	0.2	0.04	0.01	744	764
13CrMo4	0.16	0.3	0.7	1,1	0,5	0.04	0.01	747	845
S235JRC	0.17	0.2	0.8	x	x	0.02	0.01	714	833

The data on their compositions given in their data sheets were input in JMatPro software to compute their CCT diagrams, A_{c1} and A_{c3} temperatures (Figure 2). The primary difference between the 42CrMo4 and 13CrMo4 grades was the level of carbon. Unlike S235JRC steel, 13CrMo4 grade is alloyed with chromium and molybdenum [8]. This similar chemical composition between pairs of steels differing either in carbon content or in alloying element content was the main reason for their choice.

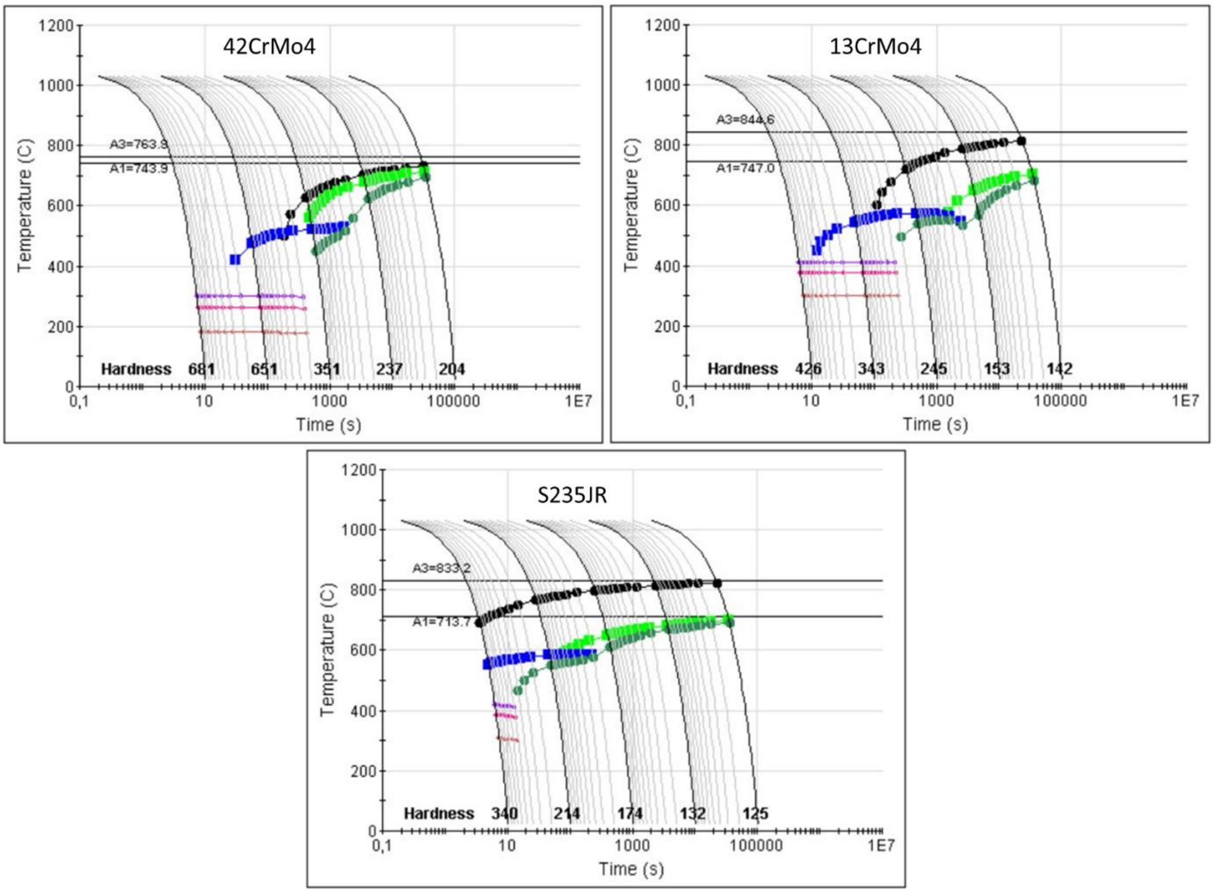

Figure 2. CCT diagrapms of experimental steels.

The as-received 42CrMo4 was in the quenched and tempered condition. Its microstructure consisted of tempered martensite (Figure 3a). 13CrMo4 contained a ferritic-pearlitic microstructure. Pearlite was globular (Figure 3b). The as-received condition was the condition after annealing. The as-received microstructure of S235JR consisted of ferrite and pearlite. In this case, pearlite was lamellar (Figure 3c).

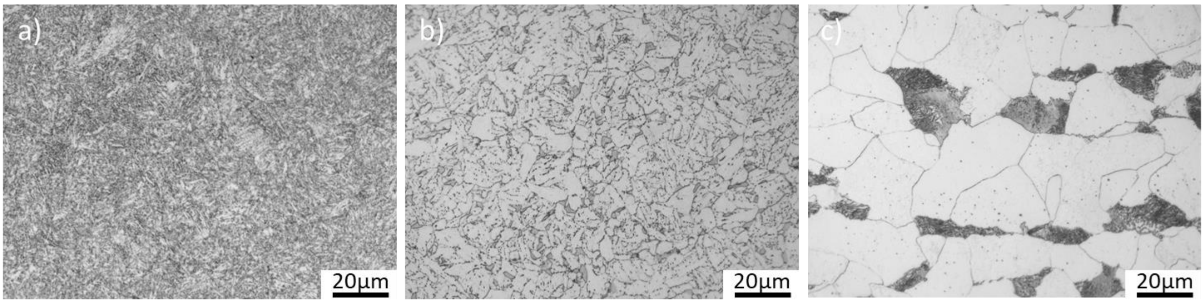

Figure 3. Micrographs of the materials in the initial condition: a) 42CrMo4, b) 13CrMo4, c) S235JR.

The material for experimental processing was bars 1000 mm in length and 30 mm in diameter. Three different configurations of induction coil power settings were proposed. In the first two configurations, both induction heating coil circuits were active. In the last configuration, only the first circuit was active. The other was set to the minimum power (Table 2). The bars were moving along the roller track at a speed of 135 mm/s, as the rollers were revolving at 20 rev./min. Temperature was measured using a pyrometer at the exit from the induction heating module. This means that the surface temperature of the bars was measured.

Table 2. Coils power settings.

Sequence	Coils 1 – 4 [%]	Coil 5 [%]
IH1	95	90
IH2	75	70
IH3	75	5

3 Results and discussion

Microstructures of the heat-treated specimens were examined using a light microscope. Their hardness was determined and reported using HV10 Vickers hardness number.

In configuration IH1, where the coil power setting was the highest, the surface temperature of bars of 42CrMo4 steel at the exit from induction heating was 850 °C. The resulting microstructure was martensitic with ferrite (Figure 4a). Hardness at the surface of this bar was 610 HV10 (Table 3). In agreement with the operation of induction heating, which heats material from the surface towards the core, the amount of martensite was decreasing from the surface to the centre of the bar. Accordingly, hardness dropped to around 510 HV10 (Table 3). In the second configuration, IH2, in which the power of induction heating coils was reduced, the surface temperature was no more than 730°C (at the same speed of feeding through the coils). The A_{c1} temperature, which is 744°C, was not exceeded. The microstructure consisted of martensite, a small amount of ferrite, and globular cementite (Figure 4b). The surface hardness was 375 HV10. Hardness values decreased towards the core, where the value was 255 HV10, which was due to a reduced amount of martensite (Table 3). In the last heating coil configuration, IH3, the power setting of the first four coils was 75%, whereas the last coil was set to 5%. The purpose was to ascertain the impact of heating by the last induction heating coil on the final temperature of the stock. At the exit from the coils, the surface temperature of the bar was a mere 620°C. The treatment in this configuration led to tempering of martensite. The final hardness was 260 HV10 (Figure 4c, Table 3).

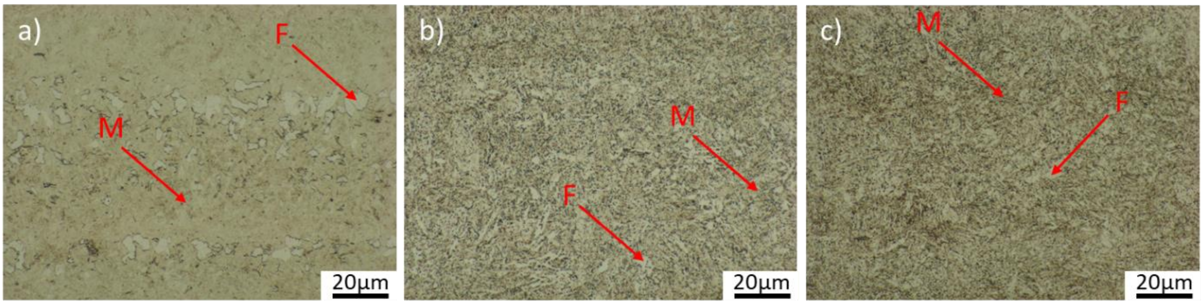

Figure 4. Microstructures at the centre of 42CrMo4 steel specimens after heat treatment: a) IH1, b) IH2, c) IH3.

13CrMo4 grade contains less carbon than 42CrMo4. The treatment with heating coil settings according to IH1 configuration led to a surface temperature of 870°C. With this configuration, a ferritic-martensitic microstructure was obtained (Figure 5a). Hardness was 215 HV10 (Table 3). Using the second heating coil configuration, IH2, which involved a reduced power settings, the steel was heated to 780°C. The resulting microstructure consisted predominantly of ferrite, with a fine dispersion of globular cementite, and a very small amount of martensite (Figure 5b). Hardness was approximately 175 HV10 (Table 3). The last configuration, IH3, involved heating by the first heating coils only. It led to no significant changes in the initial microstructure, producing ferrite and pearlite. Pearlite was globular (Figure 5c). Hardness was approximately 165 HV10 (Table 3).

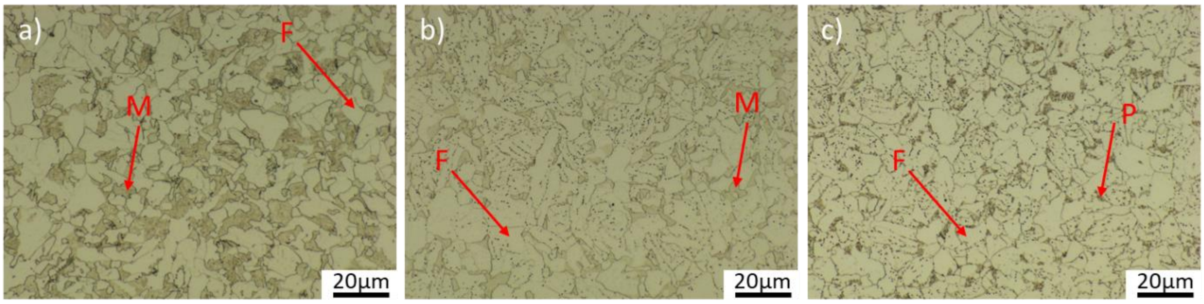

Figure 5. Microstructures at the centre of 13CrMo4 steel specimens after heat treatment: a) IH1, b) IH2, c) IH3.

S235JR grade was not alloyed with chromium. The heating configuration IH1 led to a temperature of 875°C. After subsequent quenching, the material contained ferrite and small portions of pearlite and martensite. Towards the core of the bar, the amount of martensite decreased, whereas that of pearlite increased. The hardness in the core was 156 HV10 and that at the surface of the bar was 193 HV10 (Figure 6a, Table 3). Heating configuration IH2 led to a surface temperature of 780°C. The microstructure was predominantly ferritic-pearlitic with a small fraction of martensite. Hardness levels were between 166 and 173 HV10 (Figure 6b, Table 3). Configuration IH3 led to a surface temperature of 670°C and to a ferritic-pearlitic microstructure. Its hardness was approximately 158 HV10 (Figure 6c, Table 3).

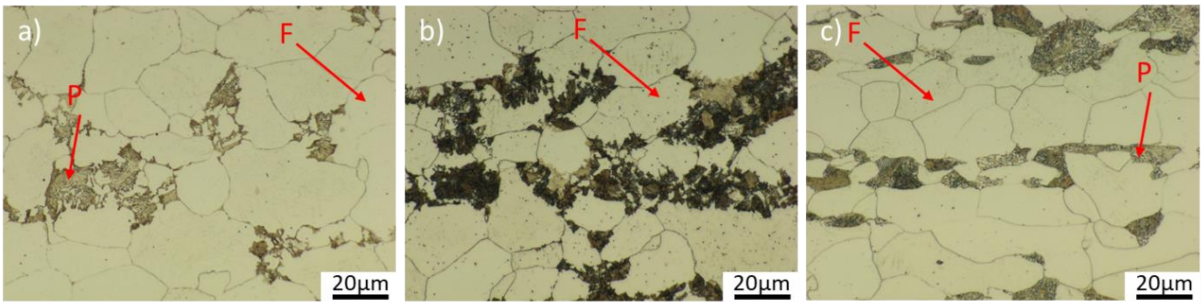

Figure 6. Microstructures at the centre of heat-treated S235JR specimens: a) IH1, b) IH2, c) IH3.

The resulting temperatures, microstructures and hardness levels suggest that chemical composition of the stock has a major impact on the outcome of heating in induction coils (Table 3).

Table 3. Results of the experimental programme.

Material	**T [°C]**	**IH1** **HV10**		**T [°C]**	**IH2** **HV10**		**T [°C]**	**IH3** **HV10**	
		Core	Surface		Core	Surface		Core	Surface
42CrMo4	850	613	510	730	385	252	620	251	266
13CrMo4	870	230	202	780	196	173	660	171	156
S235JR	875	193	156	780	173	166	670	159	157

42CrMo4 steel contains higher amounts of carbon and chromium and was heated to the lowest temperatures. One can therefore presume that with increasing levels of carbon and other alloying elements, either higher induction heating power must be used to heat up steel sufficiently or the speed of stock passing through the induction heating equipment must be reduced. As expected, induction hardening has not produced hardening microstructures in the low-carbon steels 13CrMo4 and S235JR. The main reason was the low carbon level. Hardening steels generally contain more than 0.2% carbon.

4 Conclusions

This experiment revealed that in order to perform effective induction hardening in the HDQT-R 30-12 equipment, its induction heating coil settings must reflect not only the input diameter but also its chemical composition. 42CrMo4 grade steel is suitable for induction hardening. When heat treated in this equipment, it can develop hardening microstructures with a hardness exceeding 500 HV10 in the core of bars and more than 600 HV10 at the surface. In order to achieve full austenitization, the induction coil power should be increased or the speed of feeding the bars through the coils. 13CrMo4 and S235JR steels are not suitable for induction hardening, mainly due to their low carbon content, which reduces their ability to develop hardening microstructure. They were chosen for these experiments in order to ascertain the effect of the level of carbon and other alloying elements on the ability of material to be heated by induction heating coils. The findings show that the same inductor setting lead to higher temperatures in steels with lower levels of carbon and alloying elements. Further investigation will be devoted to the HDQT-R 30-12 equipment, primarily to the selection of materials and equipment settings leading to desired microstructures.

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