

An Analysis of Induction Hardening of Ferritic Ductile Iron

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Achievements of the induction hardening of ferritic ductile iron were investigated. Ductile iron is not advisable for use in induction hardening because of the small carbon content in the metal matrix of ferritic ductile iron. The carbon content in the metal matrix of ductile iron can be increased by additional preparation of metal matrix before final induction heat hardening. Wear resistance of the induction hardened ferritic ductile iron can increase as result of increased carbon content of the metal matrix and higher hardness after induction hardening. Some heat pretreatments for metal matrix preparation were applied before the induction hardening of ferritic ductile iron. The process parameters of the induction hardening heat pretreatment were analyzed and optimized. According to recommended elemental composition of ferritic ductile iron and required mechanical properties, the process parameters of the investigated induction heat pretreatment were optimized. The efficiency of pretreatment processes of induction hardening was analyzed. Applicability and manufacture ability of engineering components by proposed heat pretreatments were investigated. The limitations of the investigated heat pretreatment applications were estimated by the comparison of mechanical properties of heat-treated specimens.

Keywords ductile iron, ferritic iron, induction hardening, metal matrix

1. Introduction

Ductile irons have become a very popular topic as a result of their unique combination of high strength and toughness. This interest is to be expected because of the favorable combination of strength, toughness, and wear resistance that can be obtained from various grades of ductile iron compared with the conventional grades of metal alloys.

The interest worldwide is to develop ductile iron with good machinability, high toughness, and high wear resistance. Because of the high ductility and good machinability of ductile cast iron with ferritic matrix in comparison with that of low carbon steel, ductile cast iron with metal matrix has great utility. Conversely, it has low strength, low surface hardness, and poor wear resistance. Attempts to increase the wear resistance of ferritic ductile iron by application of surface induction hardening are not always successful.

Induction hardening consists of rapid heating of the thin surface layer above the transformation temperature (denoted by $A_{1,2}$ on the stable Fe-C phase diagram), at which the metal matrix will be transformed to austenite and subsequent cooling of the workpiece produces a martensitic microstructure of great hardness in the thin surface layer.[1,2] Induction heat treatment has the ability to limit the heated surface area and depth of hardening only to the areas where the metallurgical changes are desired. Both the abrasive wear resistance and residual compressive stresses in the specified areas of the part increase by localized induction hardening. The remaining parts of the workpiece are unaffected by the process.

The quality of the induction-hardened layer is defined by its shape, depth of hardening, and surface hardness. The quality of surface induction hardening of ductile iron depends on two groups of influencing factors. One group comes from workpiece properties, and includes the prior microstructure, the shape and dimensions of casting component, chemical composition and amount of dissolved carbon in metal matrix, austenitizing temperature, and the cooling rate that is in accordance with rapid heating and elemental composition of ductile iron. Conversely, influencing parameters that depend on the induction hardening system are power and working frequency of a power supply and heating method. In addition, shape, dimensions, and position of the coil depend on workpiece shape and quenching parameters that include the method of quenching, type and composition of quench media, and quench pressure.

Because of the rapid increase of workpiece temperature by induction heating, there is insufficient time for dissolution and diffusion of carbon into austenite. Compared with required duration of austenitizing of quenched and tempered ductile iron or ductile iron with pearlitic prior structure, duration of austenitizing of the ductile iron with ferritic matrix must be longer and austenitizing temperature must be higher. Longer holding times and higher temperature are required for additional dissolution of car-

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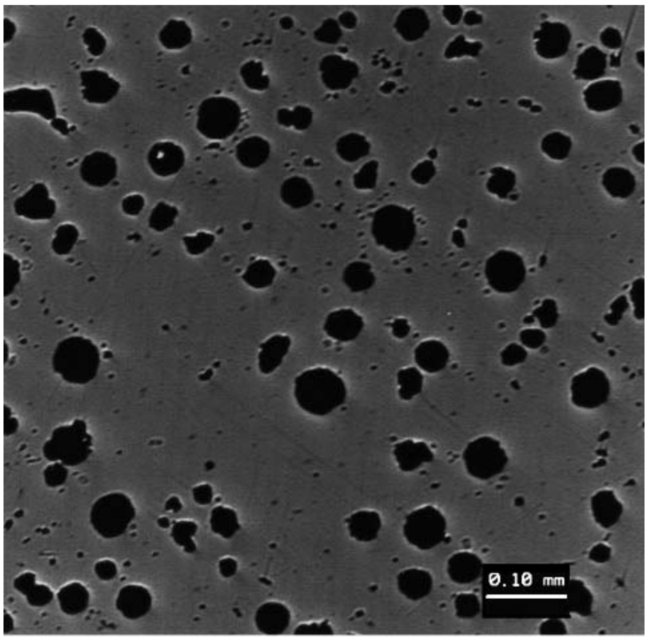
Table 1 Chemical Composition of Investigated Ferritic Ductile Iron (wt.%)

C	Si	Mn	Mg	S	P	Ni	Cu	Other
3.64	3.13	0.16	0.04	0.01	0.03	0.04	0.06	<0.05

bon into metal matrix from the graphite nodule.[3] For fully hardening ductile iron with ferritic matrix, the holding time at 870 °C must be more than 5 min. After austenitization between temperatures of 845 and 900 °C and water quenching, the surface hardness of ductile iron with predominantly ferritic matrix is less than 55 HRC. Required carbon dissolution time is shorter if the austenitizing temperature was equal to 900-950 °C; for example, dissolution time could be less than 10 s.[4]



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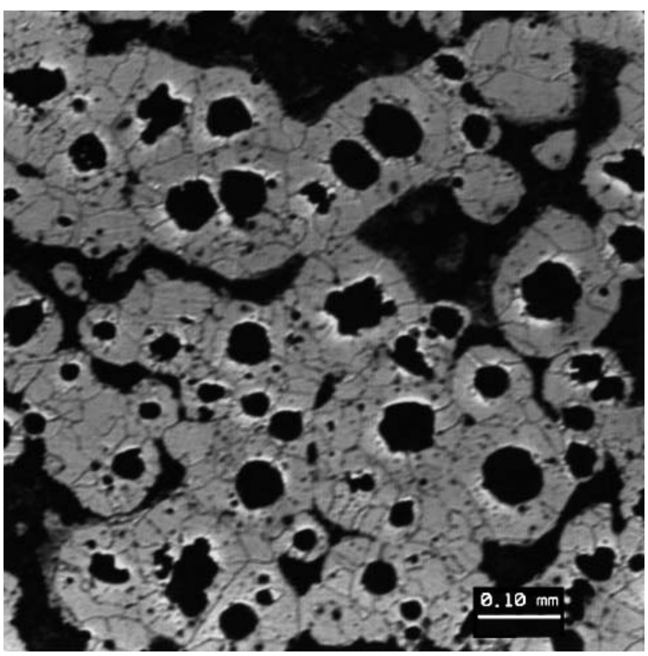
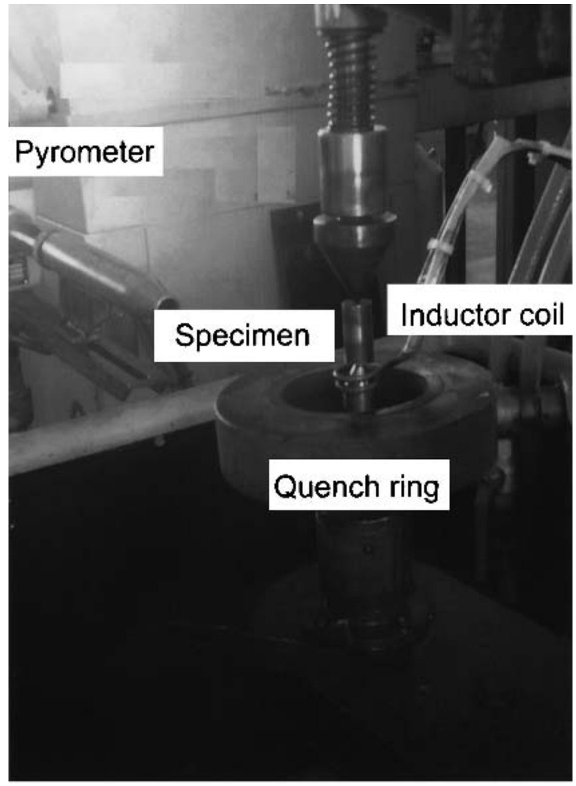


(b)

Fig. 1 Optical micrographs of initial microstructure of investigated ferritic ductile iron 100×. **(a)** Graphite nodule, polished; **(b)** as-cast microstructure of ferritic ductile iron, etched by nital 3%.



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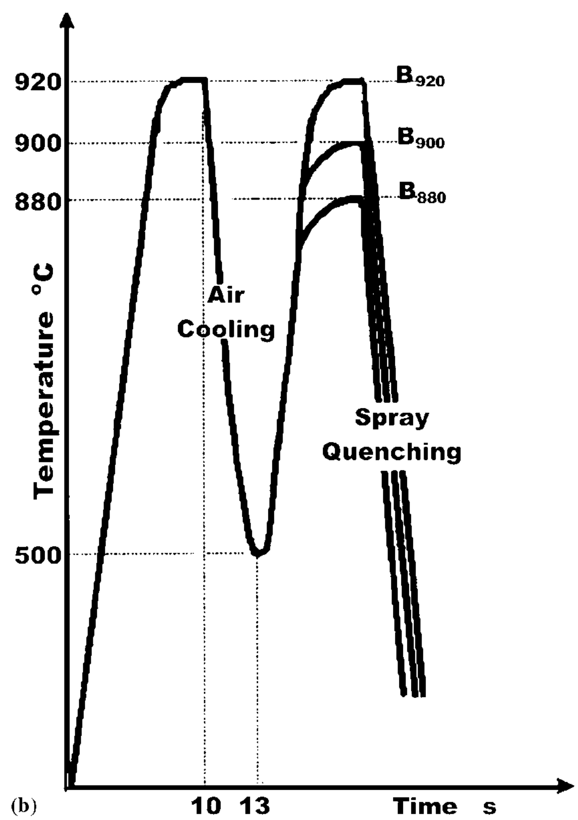

(b)

Fig. 2 **(a)** Induction hardening setup with specimen into inductor coil. **(b)** Process signature for induction pretreatment and surface hardening for specimens B_{880}, B_{900} and B_{920}.

2. Materials

Specimens of the ferritic ductile iron were produced in a commercial foundry. The chemical composition of the iron is given in Table 1. Specimens (sized 23 × 21 × 180 mm) were sectioned from the Y-probe, and the cylinder specimens ∅18 × 50 mm were machined from the larger sections. Surface quality was N6. As-cast microstructure of the investigated ductile iron consisted of 13% graphite nodules and a metal matrix that was predominantly ferritic (72%), with a small portion of pearlite (15%) (Fig. 1). Hardness of the ductile iron as-cast microstructure was equal to 156 HB.

3. Experimental Procedure

Specimens of as-cast ductile iron were induction heated in accordance with the recommended experiment plan shown in Table 2. Different initial microstructures before induction hardening were achieved by different pretreatments.

Induction hardening was done by single-shot method by the vacuum-tube-type of high-frequency generator at 50 kW and 410 kHz (Fig. 2a). A two-turn coil was used. The generator power was constant during the experiment; for specimens A and B, it was 10 kW, and for specimen C, it was 12 kW. The temperatures of specimen surfaces were measured by an optical pyrometer. Heating of Specimen A was stopped at surface temperatures of 900 or 950 °C. Specimens were spray quenched by 15% polymer solution poly-oxyalkylene glycols (PAG). After induction hardening, all specimens were tempered at 200 °C for 2 h.

The carbon content of metal matrix was increased by special, but simple pretreatments of induction heating. Specimens were heated to a maximum temperature of 950 °C when the probability of remelting of the surface was not too high. After that, specimens were cooled in air to 400 °C. When the surface temperature was 400 °C, specimens were induction reheated to the recommended temperature of austenitizing and quenched in the standard manner. Specimen A was directly quenched from 950 °C.

Induction-hardened specimens were metallographically analyzed. The graphite portion in the initial microstructure was determined by an image analyzer. Maximum surface hard-

Table 2 Process Parameters and Results of Induction

Process Parameters of the Inducton Preheating	Specimen	Process Parameters of the Inducton Surface Hardening	Surface Hardness after Induction Hardening (HRC)
Without pretreatment (as cast)	A_{900}	900 °C/11.8 s/spray quenching 15% PAG in water	50
	A_{950}	950 °C/16 s/spray quenching 15% PAG in water	59 (surface remelting)
920 °C/10 s/air cooling to 500°C/13 s	B_{880}	500 to 880 °C/4.8 s/spray quenching 15% PAG in water	54
	B_{900}	500 to 900 °C/5 s/spray quenching 15% PAG in water	56
	B_{920}	500 to 920 °C/5.8 s/spray quenching 15% PAG in water	57
950 °C/9 s/air cooling to 400°C/15 s	C_{900}	400 to 900 °C/5 s/spray quenching 15% PAG in water	60
	C_{950}	400 to 950 °C/8 s/spray quenching 15% PAG in water	60 (surface remelting)

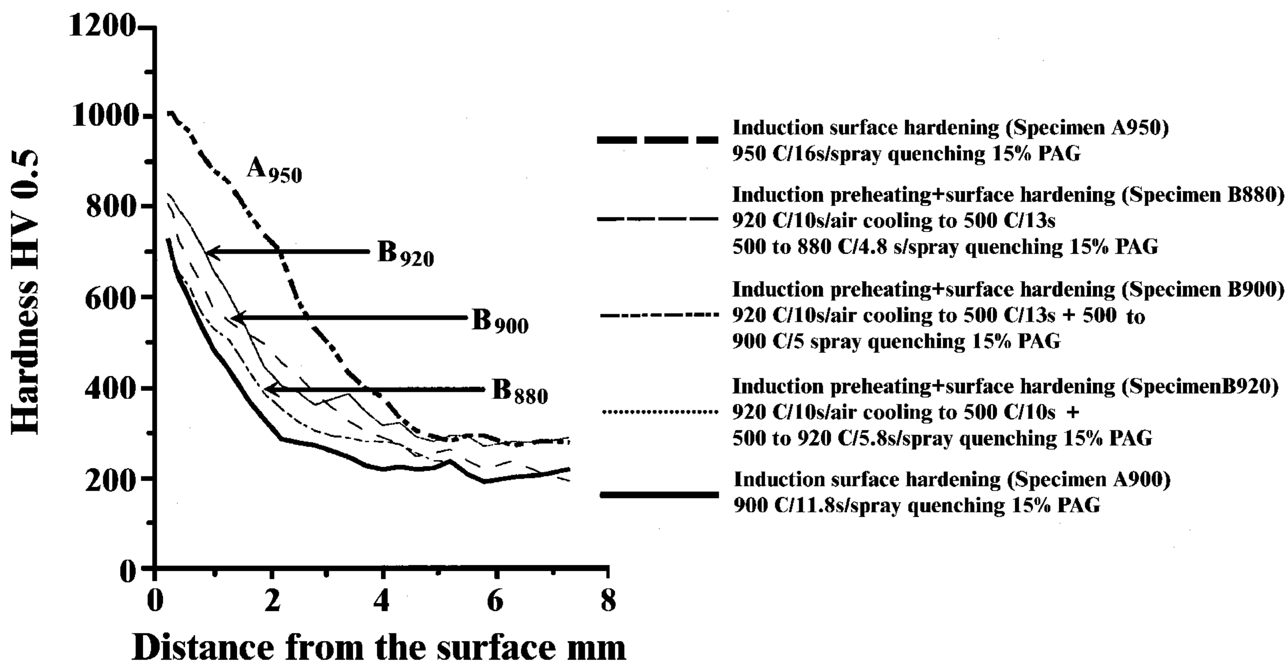

Fig. 3 Case hardness patterns of induction surface-hardened ferritic ductile iron

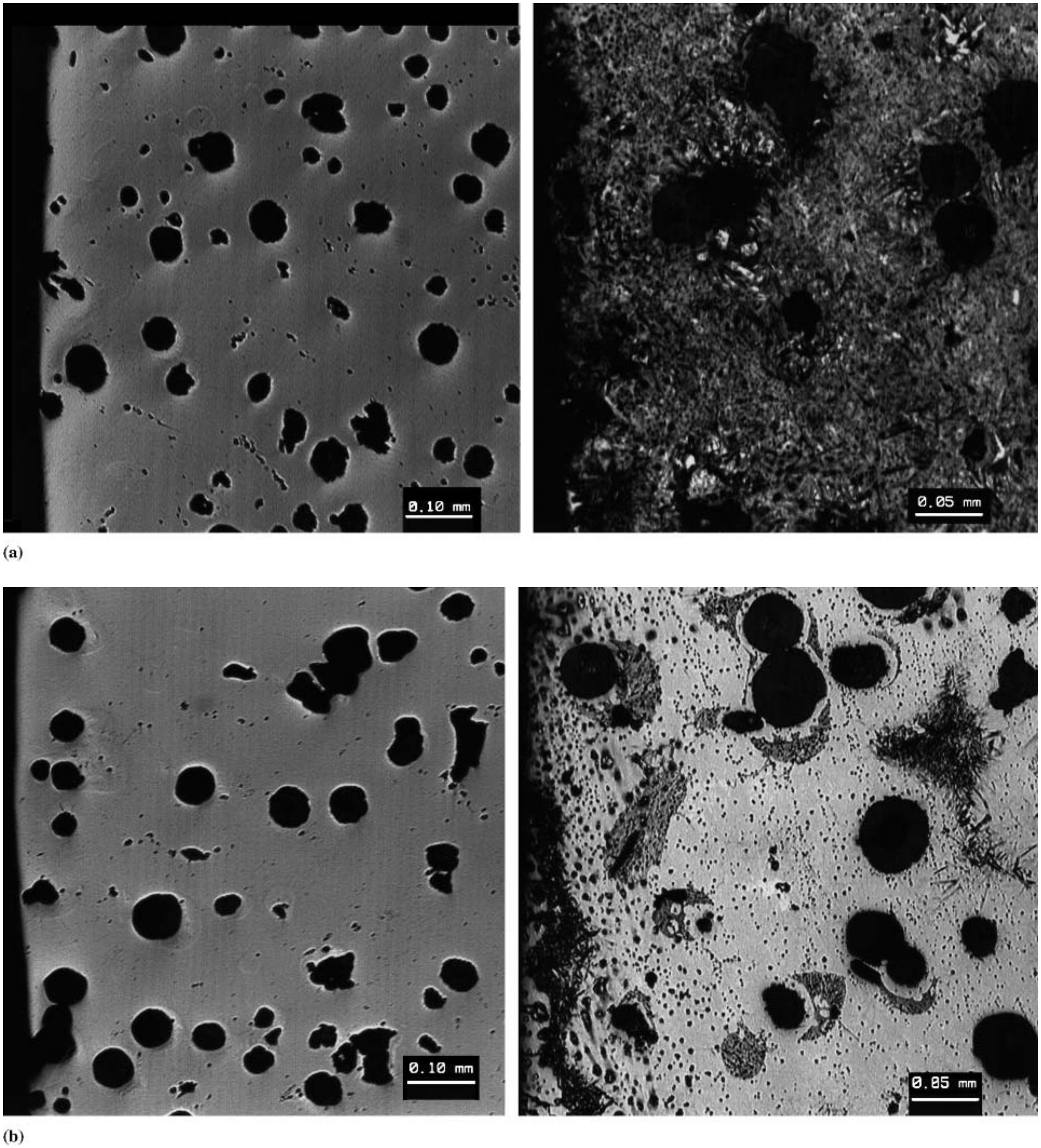

Fig. 4 Microstructure of heat-treated ferritic ductile iron. **(a)** Specimen A_{900}, inductive hardening of as-cast ductile iron; **(b)** specimen B_{920}, inductive hardening of inductive preheated ductile iron.

nesses of heat-treated specimens were tested using the Rockwell C method, and in addition, a profile of microhardness of the hardened surfaces was determined.

4. Results and Discusion

Results of surface hardness testing are shown in Table 2. The lowest hardness of 50 HRC was achieved by induction hardening of the as-cast specimen. Heating the specimen at a higher austenitizing temperature remelted a small surface layer of the specimen.

The higher surface hardness of the as-cast specimen was achieved by the inductive preheating of specimens at 920 °C/10 s and air cooling to 500 °C, followed by induction austenitizing and quenching. The final hardness results of induction hardening after induction preheating were not affected by the differences of austenitizing temperature. The surface hardness of specimens was similar after quenching from temperatures at 880 °C (54 HRC), 900 °C (56 HRC), and 950 °C (57 HRC).

The best carbon dissolution conditions were achieved by preheating the specimens to the maximum temperature, 950 °C/9 s, and by prolonged cooling to 400 °C in air. After that, maximum surface hardness of 60 HRC was achieved by the inductive hardening with austenitizing temperature of 900 °C. The surface was remelted at a higher austenitizing temperature. Case-hardness patterns of investigated induction treatments are shown in Fig. 3.

The depths of hardened layers of induction-preheated specimens are wider than those of induction-hardened specimens with as-cast microstructure, due to higher heat accumulation and higher carbon solution in austenite during the double induction heating (Fig. 3). Figure 4 shows microstructure of investigated ductile iron.

For the as-cast state of ferritic ductile iron, the induction-hardened layer was of martensite microstructure, but with hardness of 50 HRC (Fig. 4a). Hardness of the induction-hardened layer was 54-56 HRC by the induction preheating at 920 °C/10 s. The surface layer was remelted and graphite was practically disappeared during the induction preheating at the maximum temperature of 950 °C/9 s and cooling to 400 °C/15 s. The hardness of the induction-hardened layer in this case was 60 HRC.

5. Conclusions

The ferritic ductile cast iron has great utility in comparison with that of low carbon steel, due to the high ductility and good machinability of the ferritic matrix. The production of ferritic ductile iron and engineering components that are cast of ferritic ductile iron is usually much easier than that of pearlitic ductile iron. Conversely, ferritic ductile iron has poor strength, low surface hardness, and poor wear resistance in comparison with pearlitic ductile iron.

A slight increase in wear resistance of ferritic ductile iron can be achieved with common induction hardening. There is insufficient time for dissolution and diffusion of carbon into austenite because of the rapid temperature increase during the induction heating. Martensite of the surface layer has low carbon content and low hardness.

The additional carbon content in the metal matrix can be achieved by induction preheating. Induction preheating is a very simple process and can be integrated into the manufacturing processes.

The hardenability of ferritic ductile iron was increased in a relevant way by induction preheating and cooling in air before the induction hardening. The structure of specimen core was not affected.

Surface hardness combined with the hardness profile of the surface layer of ferritic ductile iron was better if the austenitizing temperature of induction preheating was higher, and cooling time in air was longer before the final induction hardening.

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