KINETICS OF INDUCTION HEATING AND METHODS OF CONTROL OF INDUCTION HEATING FOR SURFACE QUENCHING

K. Z. Shepelyakovskii

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The kinetics of induction heating for surface quenching of steel depend on factors: 1) which induce changes in the electric and magnetic parameters of steels as the result of the increased temperature (these changes lead to changes in the amount of absorbed heat at a given intensity of the electric field at a given induction current) and, 2) on factors which are responsible for the change of the intensity of the electromagnetic field during heating (i.e., change of the current in the inductor).

TABLE 1.

Parameters for the point A (Fig. 2)	Heating according to the convex curve, 1-1	Heating according to the concave curve, 2-2
Total heating time, sec	7.1	7.1
Heating time at temperature of phase transformations, sec	4.5	4.5
Final temperature, °C	1100	1105
Average heating rate at temperatures of phase transformations, deg/sec	75.5	76.5
Total depth of the quenched layer, mm	8.4	6.6
Depth of the martensite layer, mm	6.3	5.2

These factors are related to the change in the parameters of the inductors during the heating of steel and to the peculiarities of a given design of the high-frequency apparatus, i.e., whether the power utilized is regulated during the heating process. In most cases the intensity of the electromagnetic field of the inductor does not remain constant during heating, and this change affects the shape of the temperature-time curve.

The first groups of factors was investigated in [1].

The study of the effect of the second group of factors on the kinetics of induction heating is very useful, since it should make it possible to find methods of controlling induction heating during heat treatment.

The rate of heating during phase transformation does not remain constant when modern high-frequency installations utilizing either mechanical or tube generators are used. The shape of the curve representing the increase in temperature as a function of time depends on the parameters of the apparatus, on the control mechanism, and on the power level. This curve is "convex" when the rate of heating decreases after the beginning of the phase transformation, or "concave" when the rate of heating gradually increases in the phase transformation temperature range (Fig. 1). Quite often the curve has a convex, concave, and linear section.

Observations showed that the shape of the temperature-time curve changes with the tuning of the equipment and also as the result of relatively small changes in the parameters of high-frequency stepdown transformers (when these transformers are overhauled or replaced). Usually the thermal parameters in induction heating are considered to be the average rate of heating in the temperature range of phase transformation and the final temperature. However, it is not sufficient to take these two factors alone into account. The rate of phase transformations, and consequently the resulting structure and the depth of the quenched layer, depends on changes in the rate of heating, i.e., on the shape of the temperature-time curve.

The samples of steel No. 45, 30 mm in diameter, were subjected to surface quenching by heating with a current with a frequency of 8000 Hz (Fig. 2). All the heating conditions must be identical at point A (Fig. 2), since the final temperature and the average heating rate in the temperature range of phase trans-

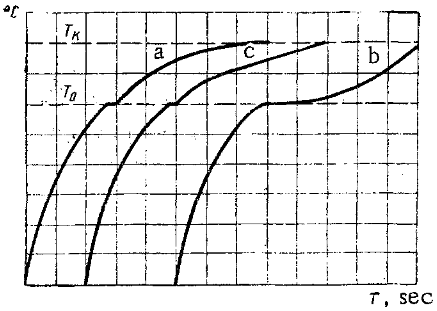

Fig. 1. Temperature-time curves resulting from induction heating. a) Convex curve—the heating rate decreases continuously after the beginning of phase transformations; b) concave curve—the heating rate increases after the beginning of phase transformations; c) combination of convex and linear sections (T_0T_K is the temperature range of phase transformations).

formation are the same in both cases. However, Table 1 shows that these conditions are not equivalent. When the samples are heated to 1100°C at an average rate of 75 deg/sec following the convex curve the thickness of the quenched layer is 8.4 mm, while heating, corresponding to the concave curve, produces a quenched layer with a depth of 6.6 mm. The optimum temperature ensuring needle-free martensite is 915°C for the convex curve and 870°C for the concave curve.

Thus, to obtain reproducible results for surface quenching, as regards the depth, hardness, and structure of the layer, not only the final temperature and heating rates must be the same but also the shape of the heating curve.

It must be kept in mind that the amount of power provided by the generator and transmitted to the machine part does not remain constant during induction heating (Fig. 3). To obtain a reproducible shape and level of the temperature-time curve one must ensure the reproducibility of the shape and level of the curve representing the variation of power with time.

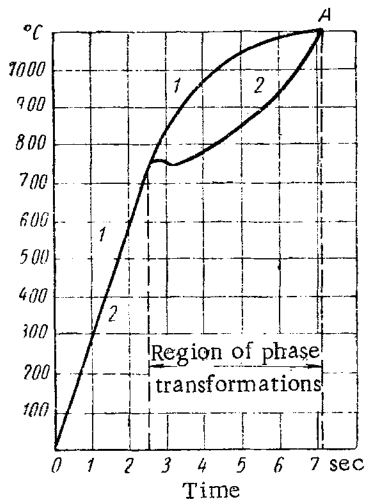

Fig. 2. Quenching of steel after induction heating following the temperature-time curves of different shapes. 1) Convex curve; 2) concave curve.

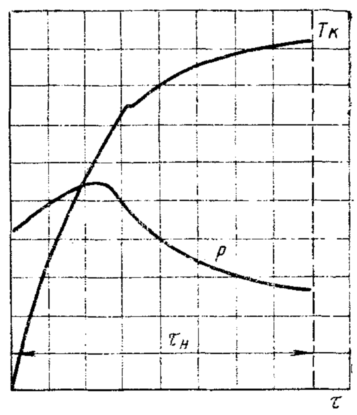

Fig. 3. Variation of the condition parameters during induction heating. T) Temperatures; τ_H) time; p) power from the generator.

At the present time curves of constant shape are obtained with equipment operated by ordinary generators by maintaining constant the current energizing the generator or by stabilizing the voltage of the generator by electromagnetic or magnetic amplifiers.

The rate of heating and the shape of the temperature-time curve change considerably if even some of the capacitors of the stepdown transformer in the generator circuit are replaced by other capacitors with the same nominal parameters, the working conditions of the generator remaining the same. Therefore, when one generator is replaced with another or some of the capacitors are replaced with others, then the apparatus must be readjusted to obtain the same heating conditions.

This is a great inconvenience of induction heating, since reproducible results can be obtained only with the same inductor and the same circuit.

The method of induction heating can be improved and made more universal if the shape of the temperature-time curve and the heating rate are kept constant by stabilizing the electric parameters directly at the inductor instead of at the generator.

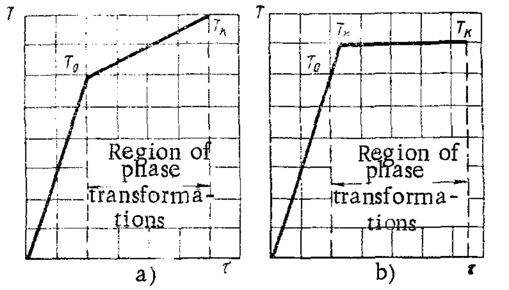

Fig. 4. Shapes of temperature-time curves in the case of the universal method of control of induction. a) Heating rate in the temperature range of phase transformations; b) isothermal heating at the final temperature.

This method of induction heating can be achieved by automatic stabilization: 1) of the current in the inductor or the voltage on the inductor during the whole heating operation, and 2) automatic stabilization of the current in the inductor or the voltage on the inductor during two or several periods of time (steps).

When the number of steps is large (ten, for example) one can vary the intensity of the current and the voltage on the inductor in a predetermined way and thus obtain a temperature-time curve of the desired shape.

The rate of heating achieved by this method is reproducible for a given inductor and a given frequency connected to any high-frequency generator with adequate power. These methods of heating can be called semi-universal methods, because at every given value of voltage or current in the inductor, the level and shape of the temperature-time curve are reproducible independently of the tuning of the equipment and depend only on the size of the inductor and the machine part.

Semi-universal methods of induction heating in which the control of heating conditions is based on the parameters of the inductor are an improvement over individual methods of control. Nevertheless, the semi-universal methods remain specific for each machine part and inductor.

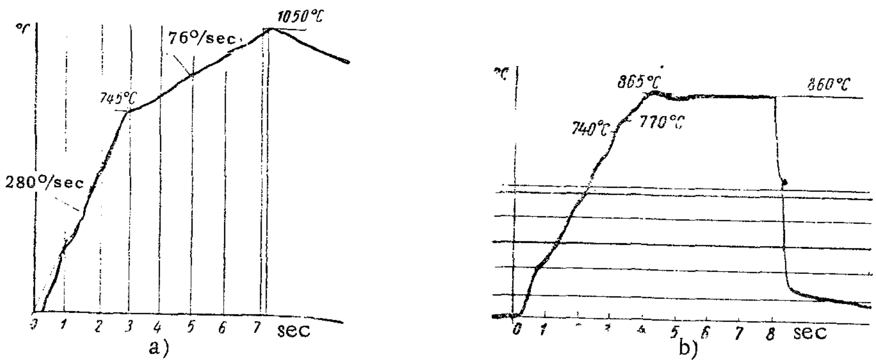

Fig. 5. Oscillograms of temperature-time curves in the case of universal methods of control of induction heating. a) $V_{\varphi} = \text{const}$; b) $T_k = \text{const}$.

It would be desirable to develop a method of controlling induction heating which would make it possible to reproduce specific heating conditions with any given inductor and any high-frequency circuit generating the same frequency. For this purpose one should use relatively simple temperature-time curves with the following characteristics: a) the heating rate in the temperature range of phase transformations must have a constant value (Fig. 4a), or b) isothermal heating at final quenching temperatures must be used (Fig. 4b).

For better reproducibility of the results of quenching (depth of the quenched layer, for example) the temperature curve must be reproducible not only in the temperature range of phase transformations but also at temperatures preceding these transformations. The rate of heating up to the temperature of isothermal heating (the T_0T_k section of the curve) must be the highest possible so that phase transformations occur mostly during isothermal heating (the T_kT_k section).

Reproducibility of the results of heat treatment can be achieved by the use of a standard shape of the temperature-time curve and optimal temperatures. Under these conditions the results of heat treatment (the depth of the quenched layer, or the structure, for example) can be reproduced with any inductor with any sufficiently powerful equipment providing the desired frequency. Such a method can be called universal.*

* The equipment and the electric circuits for the control of induction heating was developed in the department of automation and telemechanics of the Moscow Energy Institute under the direction of A. V. Netushil and M. B. Kolomeitseva and at the V. P. Vologdin NIITVCh under the direction of A. V. Bamuner together with the members of the electronics section of ZIL.

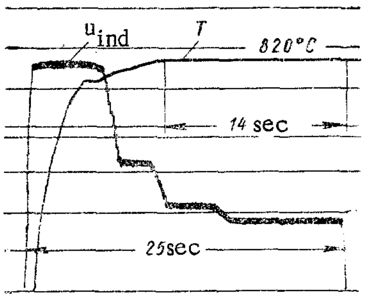

Fig. 6. Oscillograph of the temperature-time curve and the corresponding variation on the inductor with time during isothermal heating of gears 150 mm in diameter (modulus 3.75 mm).

Temperature-time curves obtained as the result of automatic control of induction heating with a 100 kw generator (8000 Hz) are shown in Fig. 5. Figure 5a refers to a constant rate at phase transformation temperatures (745-1050°C). The rate of heating preceding phase transformation is 280 deg/sec, and the rate of heating during phase transformation is 76 deg/sec. The possible maximum rate depends on the maximum power which can be applied to a unit volume of steel, i.e., on the ratio between the size of the machine part and the power of the generator.

When ordinary methods of controlling induction heating are used the temperature of the steel increases continuously during phase transformation. The new method of regulating and controlling induction heating makes it possible to use isothermal heating. An oscillogram of this type of heating is shown in Fig. 5b. The first stage—heating to 850°C—lasts 4 sec, and the second stage—isothermal heating at 850°C—also lasts 4 sec.

Both of these heating methods (isothermal heating or heating at a constant rate) have different applications. High ultimate strength and high impact strength result from minimum quenching temperatures, resulting in needle-free martensite [2, 3]. Overheating by induction sharply decreases the strength of the quenched layer [4], and, as a result, the probability of quenching cracks increases. Therefore, when the quenched layer is relatively thin (1-3 mm) it is advisable to heat the machine part at a constant rate so as to prevent great differences of temperature in the quenched layer. When the quenched layers are deeper (4-5 mm) there is danger of overheating the surface, and in this case isothermal heating is preferable. The period of time the piece is kept at the desired temperature depends on the time required for the completion of phase transformations in a layer of a given thickness. By varying the time of isothermal heating one can vary the thickness of the quenched layer.

TABLE 2

Conditions	Control steps			
	I	II	III	IV
Time, sec	0—7.0	7.0—10.8	10.8—16.0	16.0—25
Power from the generator, kW	75	40	20	15
Voltage on the inductor, V	52	32.5	20	18
Temperature, °C	20—790	790—815	820	820

Isothermal induction heating yields higher and more stable strength indices than induction heating by continuous temperature increase. In particular, steels with low hardenability should be subjected to isothermal induction heating for surface quenching [5, 6].

The temperature-time curve produced by isothermal heating at 820°C for gears with a modulus of 3.75 mm, and the variation of the voltage on the inductor corresponding to it, are given in Fig. 6. The data for this figure are given in Table 2. In this case the variation of the temperature and isothermal heating is achieved by steplike changes of the voltage on the inductor, which produces changes in the other parameters. Four steps are required to complete the cycle.

In the case of surface quenching the quality depends on the microstructure of the layer: the amount of needles in martensite, the presence of free phases (ferrite, carbides), and the thickness of the quenched layer. Different temperature-time curves and corresponding variations of the thickness of the quenched layer are shown in Fig 7. The samples were subjected to heating before quenching according to the given temperature-time curves but were kept at the quenching temperatures for different times. The results constitute the so-called "quenching series". From samples of a given quenching series one can determine the optimum heating conditions for the desired depth and microstructure of the quenched layer. The data in Fig. 7c show that one can vary the ratio between the thickness of

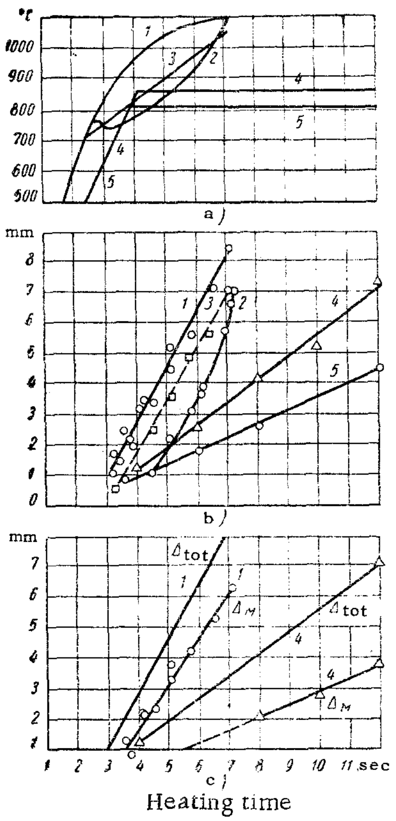

Fig. 7. Kinetics of growth of the thickness of the quenched layer corresponding to different shapes of the temperature-time curve of induction heating. 1) Heating along the convex curve; 2) heating along the concave curve; 3) heating at the constant rate of 76 deg/sec; 4) isothermal heating at 850°C; 5) isothermal heating at 810°C; Δ_{tot}–total depth of the quenched layer (down to the original structure); Δ_M–depth of quenched layer with martensite structure. a) Temperature-time curves; b) variation of the total depth of the quenched layer with the heating time; c) variation of the total depth of the quenched layer and of the layer of martensite with the heating time.

the completely quenched layer (martensite) and the total thickness of the quenched layer (martensite + transition layer) by changing the shape of the temperature-time curve, and consequently the properties of the machine parts.

The method of controlling induction heating described is convenient for the study of the kinetics of transformation and grain growth in alloys and steels, since it makes possible isothermal heating during phase transformations and reduces the heating time to a minimum.

With the new equipment we can change the heating conditions so as to follow any desired temperature-time curve. An example of automatically controlled heating including two isothermal periods is shown in Fig. 8. This method of induction heating can be used for rapid chemicothermal treatment of steels and different alloys.

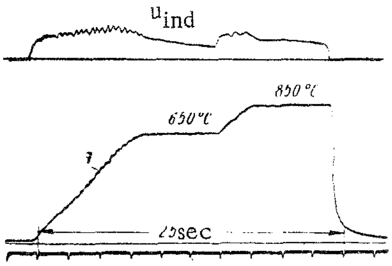

Fig. 8. Induction heating with two isothermal plateaus.

The new method of regulating and controlling induction heating, together with the new equipment, improves the heat-treatment conditions and make it possible to create universal and easily reproducible conditions, and thus produce a uniform quality in machine parts.

Conclusions

1. Under the present conditions of induction heating for surface quenching, controlled by the parameters of the generator, the temperature-time curves in the temperature range of phase transformation may be convex, concave, or both. A constant heating rate during phase transformation is seldom found in practice.

2. The rate of heating and the shape of the temperature-time curve change when a piece of equipment (generator, capacitors, high-frequency transformer) is replaced, although the working conditions of the generators are kept constant. For reproducible results in surface quenching one must reproduce not only the final temperature and the average rate of heating during phase transformation but also the shape of the temperature-time curve.

3. The new method of control ensures reproducibility of induction heating for a given machine part and for a given inductor, provided the tuning and the elements of the equipment (generator, capacitor, high-frequency transformer) remain the same. These methods are called individual methods of control.

4. Semi-universal methods of control of induction heating are based on one-step or several-step stabilization of the electric parameters of the inductor. These methods ensure complete reproducibility of heat-treatment conditions and of the results of surface quenching for a given size of the conductor and the machine part with any induction equipment, provided the current has the same frequency and the generator has sufficient power.

5. Universal methods of controlling induction heating are based on the use of rectilinear temperature-time curves with a constant rate of heating at phase transformation temperatures, or isothermal heating at the final temperature. These methods ensure complete reproducibility of heat-treatment conditions and of the results of surface quenching on any inductor and for any machine part, provided the frequency of the current is the same and the generator has sufficient power.

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TECHNOLOGY OF HEAT TREATMENT BY INDUCTION HEATING

M. O. Rabin and A. G. Orlovskii

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Induction heating in the heat treatment of automobile parts was first used at our plant. In 1937-1938 surface quenching of the necks of crank shafts of the ZIS-5 engine was developed at our plant in collaboration with the staff of the V. P. Vologdin laboratory. The equipment was installed as part of the continuous production line, in which the parts were subjected to mechanical treatment on semi-automatic high-frequency apparatus. More than 61% of all the parts of the engines of the ZIL-164A and ZIL-157K automobiles are surface hardened by induction heating.

Surface Quenching of Machine Parts After Induction Heating

Induction heating is widely used for surface treatment of parts.

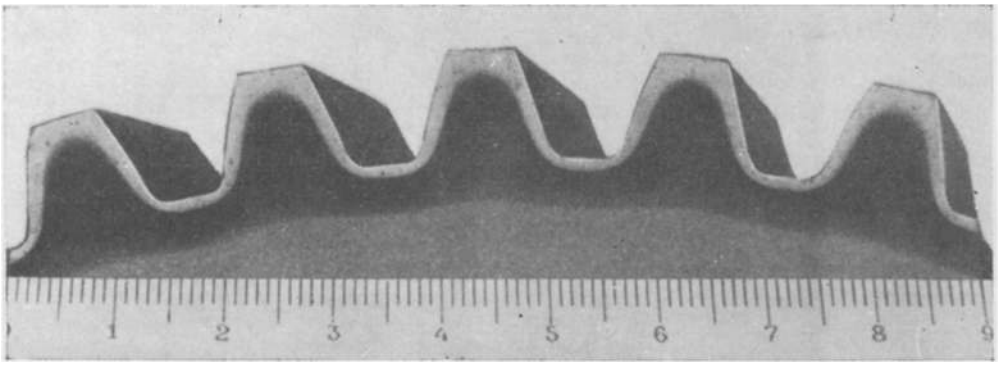

Fig. 1. Microstructure of the drive gear of the ZIL-164 automobile, made of 55PP steel, heated by induction and quenched.

The depth of the quenched layer is determined by the depth of the layer heated to the quenching temperature. Parts made of No. 45, 40Kh, 40KhNMA, and other steels are subjected to local surface quenching. Local surface