Surface-hardened parts are widely used in machine construction. However, the effect of the hard surface and the soft core on the overall quality of machine parts may differ. A difference in the ductile characteristics of the surface layer and the core when the part is stressed creates triaxial stresses in the boundary zone [1]. Fatigue cracks (Fig. 1) generally occur in this zone of surface-hardened parts subjected to alternating stresses.

Surface hardening by quenching with deep induction heating of parts made of steels with controlled hardenability has recently come into wide use [2]. This treatment provides a hard surface layer with a smooth transition to the core, which greatly increases the carrying capacity of the part.

Deep heating by means of high-frequency current is achieved due to thermal conductivity with some reduction of the specific power and is relatively easy to use for surface hardening of parts with small and moderate sizes — up to 500 mm in diameter. For large parts (for rolls 500 mm in diameter or larger, for example), which requires a deep hardened layer, current of industrial frequency is used for heating.

Surface hardening with an abrupt transition zone does not ensure the required contact fatigue strength of rolls. Rolls are frequently put out of commission due to chipping of the hardened layer. In order to ensure hardening to the full depth, with a smooth transition from the hardened layer to the core, it is necessary to heat a layer deeper than the depth of hardenability of the steel to austenitizing temperature. Deep heating by means of current of industrial frequency is also achieved due to thermal conductivity with proper selection of the specific power and heating time. For rolls of steel 9Kh2MF with a diameter of 500 mm, e.g., hardening is conducted by means of continuous successive heating with the inductor moving at a speed of 0.8–1.2 mm/sec and a power of 0.1–0.2 kW/cm² [3]. Heating under these conditions and cooling with a water spray produces a hardened layer with a structure of martensite for a depth of 12 mm and a smooth transition zone covering 20–30 mm.

Fig. 1. Fatigue failure of a surface-hardened sample 18 mm in diameter (bending with rotation).

Fig. 2. Contact fatigue strength of model rolls 90 mm in diameter of steel 9Kh with a hardened layer differing in depth. 1) 9 mm; 2) 15 mm.
To determine the effect of the depth of hardening and the transition zone on the contact fatigue strength of hardened rolls, we tested models of rolls at the Central Scientific-Research Institute of Heavy Machine Construction (TsNIITMASh) [4]. Rolls of steel 9Kh with a diameter of 90 mm were hardened in series with different heating conditions (2500 Hz). The rolls were heated to 920°C on the surface and tempered at 160°C for 4 h. Two series of five pairs of rolls with different thicknesses of the hardened layer were tested. In the first series the thickness of the hardened layer (HRC 62-60) was 4 mm, with a transition zone of 5 mm, and in the second the hardened layer was 7 mm thick and the transition zone 8 mm thick.

Figure 2 shows the test results for model rolls. The rolls of the second series, with deep and smooth transition of the hardened layer, had a higher contact fatigue strength; galling occurred to a relatively small depth in contrast to the deeper pitting of the first series of rolls (Fig. 3).

It should be noted that the structural strength of surface-hardened parts depends not only on the relationship between the thickness of the hardened layer, surface zone, and core, but also the magnitude and distribution of residual stresses [5, 6].

Induction hardening to a sufficient depth with a smooth transition zone and also bulk heating in furnaces lead in some cases to premature failure of rolls due to galling of the hardened layer [3]. Galling promotes residual tensile stresses that occur at some distance from the surface. To shift these stresses to a deeper safe zone and reduce their magnitude the rolls are first heated (through the entire section), the depth of surface heating is increased, cooling during quenching is increased through the center hole, electrotempering is used, and so on [6].

Induction hardening is achieved by proper selection of the parameters (the frequency of the current and specific power) for the formation of a hardened layer due to the difference in the cooling rate through the depth of the zone heated to austenitizing temperature. Deep heating is relatively easy by means of induction.

In conclusion, it can be stated that for induction hardening of rolls for cold-rolling mills with a diameter over 500 mm one should select steels with the highest hardenability, and the depth of the layer heated to austenitizing temperature should be larger than the hardenability of the steel, ensuring the given cooling conditions. For rolls of moderate size (100-500 mm) it is best to use steels with low hardenability, depending on the diameter of the rolls.

For rolls of small size (<100 mm), especially for three-high mills, high-alloy steels are used, permitting through hardening with a relatively favorable distribution of residual stresses through the section of the roll during bulk heating [7, 8].