It is known [1] that titanium is the most effective hardening element for high-strength maraging steels. In addition to this, titanium lowers the plasticity and toughness characteristics primarily as a result of the formation of compounds with carbon and nitrogen (carbides, carbonitrides, and nitrides).

The purpose of the present study* was to investigate the effect of titanium and heat-treatment regimes on the structure and properties of maraging tool steels 05Kh12N6D2SGTMF† (Technical Specification 14-1-3073-80).

This steel is used for components of die-casting molds in which commercial-rubber and plastic articles are fabricated. It is characterized by high dimensional stability during heat treatment and significant corrosion resistance. For the investigation, we used commercially produced steel 05Kh12N6D2SGTMF rods (smelting in open electric furnaces) of circular (150 and 50 mm in diameter) and square (160 × 160 mm) cross section and rods produced by laboratory smelting (20-kg ingots) — a 35 × 35-mm section with a titanium content of 0.21, 0.40, 0.56, and 0.92% (see Table 1).

We investigated the structure of the steel (phase composition, austenite grain, and the composition and distribution of nonmetallic inclusions) under an optical (Neophot") and electron ("Tesla BS-613", "Stereoskan") microscopes using "URS-50M" x-ray units and an "MS-46" microprobe designed by the firm " Cameca." The relative necking during delayed failure (a load-application rate of from 20 to 0.002 mm/min; other test conditions were in accordance with GOST 1497-84) was determined on a universal SP i00/i testing machine. The hardness and resilience were determined in accordance with GOST 9013-59 and GOST 9454-78, respectively, and the specific electrical resistance from a double-bridge circuit.

The study was conducted on steel specimens in the as-delivered state (after high tempering), after quenching in the 800-1000°C interval, and after quenching and aging at 490°C for 2 h.

A significant amount of nonmetallic inclusions is observed in the structure of the steel 05Kh12N6D2SGTMF specimens in the initial and heat-treated states. Typical nonmetallic inclusions are shown in Fig. 1. They are (from metallographic indications) individually arranged faceted titanium nitrides and carbonitrides of irregular shape and a dark-rose color (Fig. 1a); titanium sulfides of oval or irregular shape, frequently with serrated borders, and of a dark-rose color (Fig. 1b); fine elongated multiphase inclusions, which are hypothetically carbonitrides with oxide impregnations (Fig. 1c); and, individual point finely disperse oxide inclusions. The metallographic data confirm the results of micro-x-ray-spectral analysis. It is apparent from Fig. 2 that the titanium-containing inclusions may be either nitrides or sulfides. According to petrographic analysis, the elongated multiphase carbonitrides impregnate the oxide compounds, especially many of the compounds in melts with a high titanium content. This method indicated, however, that the fine oxide inclusions in melt 3 are titanium oxides.

It is established that the degree of contamination of the steel with nonmetallic inclusions depends on the titanium content. In the steel with 0.76% Ti, the overall amount of inclusions is 1.5 times higher than that in the steel with 0.38% Ti (3034 and 1743 in melts 1 and 3, respectively; evaluated in accordance with GOST 1778-70, method P, x520).

* N. V. Kostyuchenko, L. N. Shul'gin, and A. P. Khvalin took part in the study.
† Inventor's Certificate No. 1002396.
The microstructure of steel 05Kh12N6D2SGTMF is "displacement" martensite [1].

With a high titanium content (0.76%), a bright phase, which is elongated in the direction of deformation along the boundaries of former austenite grains is observed in the steel (Fig. 3a). It is apparently arranged nonuniformly at points of liquation of the alloying elements. The microhardness of this phase H 384 (a matrix microhardness H 260). X-ray-structural analysis indicated that the bright phase cannot be residual austenite (no austenite lines are observed on the diffraction photographs).

According to x-ray-microprobe (Fig. 4), the bright phase is enriched with ferrite-forming elements — Ti, Si, Mo, V, and Cr — and is impoverished of austenite-forming elements — Ni, Cu, Mn. The bright phase is apparently high-temperature δ-ferrite, which, according to Bityukov et al. [2], is observed in maraging steels with 12% Cr.

The presence of a larger amount of nonmetallic inclusions and δ-ferrite in steel 05Kh12N6D2SGTMF with a higher titanium content most likely contributes to retention of a fine austenite grain (see Fig. 3b) to high austenitizing temperatures (after quenching melt 3 specimens from 1250°C, the austenite grain corresponds to a No. 7 grain, and the melt 1 grain to a No. 3...4 grain). It should be that recrystallization with size reduction of the austenite grain is observed in steel D80 at a temperature of approximately 1000°C, and more notably in the steels with a low titanium content. Moreover, elongated δ-ferrite segregations are obstacles to the growth of the austenite grain in the transverse direction, and contribute to the formation of a stitched structure in the steel with the high titanium content.

It is established (Fig. 5) that the hardness of the steel in the initial state is virtually independent of the titanium content, while the resilience diminishes markedly with increasing titanium content. The effect of titanium on relative necking during delayed failure is manifested most strikingly. The relative necking determined for a load-application rate of 0.002 mm/min diminishes by a factor of 3 as the titanium content is increased from 0.38 to 0.76% (Fig. 5). It should be noted that titanium is not observed to have a pronounced effect on plasticity at the normal tensioning rate.

The hardness of the quenched steel remains virtually unchanged with increasing titanium content, and increases after quenching and aging (in this case, chiefly with an increase to 0.5% Ti). The relative electrical resistance ρ, which indirectly characterizes the saturation of the solid solution with carbon and alloying elements, varies in a similar manner. Consequently, the composition of the solid solution of the steel remains virtually unchanged with a titanium content of more than 0.5%. The resilience of the steel and the tendency to austenite-grain growth decreases with increasing titanium content.

An increase in the austenitizing temperature during equenching from 800 to 1000°C leads to a certain increase in HRC and ρ of the steel for all titanium contents investigated.

The resilience $a_1$ increases with increasing austenitizing temperature; in this case, it increases to a large degree for small titanium contents, and remains unchanged with 0.92% Ti. The most significant increase in $a_1$ is observed in the 900...1000°C interval; it is precisely in this interval that the size of the austenite grain is reduced, i.e., the increase in $a_1$ is obviously determined by the size reduction of the initial grain.