Features of the changes in structure and composition of the carbide phases and in high-temperature strength in long service under creep conditions of 12Kh1MF steel were investigated. The phase composition and structure were determined after service at various temperatures and for different times. The influence of the changes in structure on the high-temperature strength properties of the steel was established. Stress-rupture strength curves of the metal of 12Kh1MF steel steam superheaters in creep under service conditions were obtained.

12Kh1MF chrome-molybdenum-vanadium heat-resistant steel is widely used for steam superheaters of modern electric power generating equipment. The service of steam superheaters at increased temperatures under internal pressure causes the development of creep processes, the intensity of which depends upon the structural and phase changes in the steel.

For purposes of evaluation of the condition of the metal, prediction of the changes in structure and properties of the steel in service, and determination of the remaining service life of parts of long-operating power equipment the rules of change in structure, phase composition, and service properties of 12Kh1MF steel during service were investigated.

12Kh1MF steel steam superheater tubes were investigated after service for different times (from 50,000 to 200,000 h) under a steam pressure of 10-24 MPa and an operating temperature of 550-600°C. The analysis of the dislocation structure of the specimens was made on an EM-200 transmission electron microscope and the stress-rupture strength tests of the specimens were made on AIMA-5M machines.

The 12Kh1MF steam superheater tubes supplied to TU-14-3-460-75 of the Ministry of Ferrous Metallurgy were normalized with subsequent tempering at 720-750°C. This provides stabilization of the structure and phase composition of the steel. However, long service at increased temperatures leads to redistribution of the alloy elements between the solid solution and the carbide phases, accumulation and annihilation of dislocations, and migration of boundaries.

In this work an investigation was made of the kinetics of these processes in operation of 12Kh1MF steel under creep conditions. It is known [1, 2] that the processes of creep and failure are structurally sensitive and therefore the data obtained on the kinetics of the structural changes may serve as the basis for development of a method of prediction of the remaining life of steam superheaters.

Redistribution of the Alloy Elements between the Solid Solution and the Carbide Phases. Together with other factors the high-temperature strength of 12Kh1MF steel is provided by solid-solution and dispersion hardening. Alloying of the steel with vanadium promotes dispersion hardening. Other carbide-forming elements such as chromium and molybdenum increase the high-temperature strength as the result of both dispersion and solid-solution hardening. Chromium and molybdenum are stabilizers of the steel structure. After the above heat treatment chromium and molybdenum are primarily in solid solution. In aging of the steel the kinetics of precipitation of these elements into carbide phases occurs according to a C-shaped curve and depends upon time and temperature [3]. The temperature of the minimum stability of the solid solution of chromium in iron is in the service temperature range of the tubes, 550-600°C, while the temperature of the minimum stability of the α-solid solu-
tion of molybdenum in iron is somewhat higher, 650-700°C. In connection with this it was of interest to investigate the kinetics of precipitation of chromium and molybdenum from the solid solution into the carbides. During service types $M_3C$, $M_7C_3$, $M_{23}C_6$, and $M_2C$ carbides containing Cr and Mo are formed in the steam superheater metal.

Figure 1 shows the results of chemical analysis of the solid solution composition in 12Kh1MF steel after service for different times at different temperatures. The Larson-Miller parameter $P = T(\log \tau + 20) \cdot 10^{-3}$; $T$ service temperature in K; $\tau$ time.

Simultaneously with a decrease in alloy element content in the solid solution there is a decrease in the free energy of the solid solution - carbide system primarily as the result of coarsening of the particles and the increase in distance between them. Certain features of precipitation of carbides in 12Kh1MF steel should be noted. A large portion of the vanadium carbides is precipitated in the ferrite matrix, including at dislocations, and 80% of the V is contained in the carbides even after heat treatment (that is, before service). In connection with this primarily carbides containing chromium and molybdenum are precipitated at the subboundaries formed in creep.

The processes of growth of carbide particles precipitated at grain subboundaries and boundaries in the ferrite were investigated. Despite the significant dispersion it was established that during long service under creep conditions there is a tendency toward an increase in both the most probable carbide particles diameter and in the average distance between particles (Fig. 2). From a comparison of the data of Figs. 1 and 2 it may be seen that a reduction in chromium content in the solid solution to a level below the original coincides for the temperature-time parameter to the start of significant growth of the carbide particles at the grain subboundaries and boundaries and also with an increase in the distance between the carbide particles. Both of these processes are weakening ones and must cause a reduction in high-temperature strength of the steel.

Structural Changes. Deformation processes in creep depend upon the structural condition an, in turn, accelerate diffusion processes and, consequently, structural and phase changes.

The structure of the 12Kh1MF steel steam superheater metal after heat treatment consists of ferrite and tempering sorbite. After heat treatment the ferrite grains contain dispersed carbide particles, primarily VC, with an average density of distribution of 25 $\mu$m$^{-2}$. During creep further precipitation of carbides occurs. In the second stage of creep the process of formation of subboundaries decorated with dispersed carbides starts and it continues in the third stage. Precipitation of dispersed carbides and formation of sub-boundaries cause an increase in ferrite hardness. With development of creep growth of the carbide particles occurs in the ferrite. At the grain boundaries there are formed accumulations of coarse carbides around which there appear zones free of dispersed carbide particles. Embryos of recrystallization are formed in the body of the ferrite grains.