Copper radiation has been used in an x-ray study of the temperature dependence of the effective characteristic x-ray temperature $\Theta_p(T)$ for the alloys of the Cu–Ni system over the temperature range 293–1073°K and in a determination of the concentration dependence of $d\ln\Theta_p/dT$ for the alloys. It is shown that $\Theta_p(c)$ is additive. The concentration dependence of $d\ln\Theta_p/dT$ is linear. The agreement between the experimental results and data in the literature is discussed.

The dynamic properties of lattices, which are governed by the nature of the atomic vibrations about the equilibrium positions, are of fundamental importance in solid state physics. Many physical properties of metals and alloys could not be explained without an account of the vibrational motions of atoms in the lattice. An important consideration is the anharmonicity of the vibrations.

We used an x-ray method to study the thermal atomic vibrations, since the temperature dependence of the integral intensity of x-ray interference peaks is a reliable measure of these vibrations and of their anharmonicity.

A basic characteristic of the thermal vibrations is the temperature dependence of the effective characteristic x-ray temperature $\Theta_p$, or, more specifically, the temperature derivative of the logarithm of this temperature, $d\ln\Theta_p/dT$, which is a universal measure of the anharmonicity. The Debye temperature has frequently been related directly to the interatomic forces, but the x-ray temperature $\Theta_p$ cannot be related directly to these forces [1, 2], since $\Theta_p$ is governed not only by these forces, but also by the spectrum of thermal lattice vibrations, the thermal changes in the spectrum, and the thermal changes in the root mean square static atomic displacements. An unambiguous correspondence can be established between the changes in $\Theta_p$ and those in the binding forces in only the simplest cases, in which the lattice type, degree of order, etc., are unaffected by the concentration. However, a study of $\Theta_p$ is of independent value, particularly for refractory alloys, in which diffusion rates depend not so much on the interatomic forces as on the displacements of atoms from their equilibrium positions. Moreover, $d\ln\Theta_p/dT$ is a universal measure of the anharmonicity of a solid [3, 4].

We used the Debye–Waller kinematic theory of x-ray scattering, refined by Krivoglaz et al. [5] with an account of the anharmonicity of the atomic vibrations in the lattice. It has been shown experimentally [6–10] that this theory successfully describes crystals made up of either one or two atomic species.

In an evaluation of thermal atomic vibrations, particularly of the anharmonicity of these vibrations, it is extremely convenient to use $\Theta_p$, although it is always possible to directly convert to the more graphic quantity $u_g^2$ — the root mean square displacement of atoms from their equilibrium positions.

We studied alloys of the Cu–Ni system at concentration intervals at 10 at. %. In this system, the Cu and Ni atomic masses and radii differ only slightly. In addition, the system forms a continuous series of solid solutions, so the Debye–Waller theory can be used successfully. The alloy samples were synthesized from electrolytic Cu and Ni in a high-frequency oven in an atmosphere of purified argon. After forging, the samples were subjected to a diffusion annealing in vacuum for 8 days at 1000°C. The ingots were subjected
within ±2°C. A high-temperature x-ray diffraction study of an alloy of one composition was carried out several times as the sample was heated and cooled; then the sample was replaced by another of the same composition and from the same batch, and the measurements were repeated at the high temperatures. In this manner we were able to monitor the increase in the extinction effect at high temperatures due to the grain growth. In recording the diffraction patterns, we recorded lines at intervals of 25, 50, and 100°C as indicated in the figure captions.

Using these diffraction patterns, we determined the temperature dependence of the lattice constant and the relative integral intensities of the lines. For the latter purpose, we carried out a photometric study of the interference peaks from both sides. Using an integral planimeter, we found the area bounded by the density curve and the background line. We used the (331) and (420) reflections. We corrected for thermal diffuse scattering by the method of [12]. Anisotropy of the thermal atomic vibrations was neglected, since it is negligible, 1%, for relatively low reflection indices for cubic crystals [5]. The temperature dependence of the interference-peak intensities was analyzed by the approximate method of [8] with thermal expansion taken into account; the corresponding standard intensity corrections were also taken into account.

The Θ_p(T) dependence is known to be sensitive to the choice of Θ_0 (which corresponds to room temperature under our conditions). Accordingly, to find the actual Θ_p(T) dependence, we found Θ_p from the family of Θ_p(T) curves by the method of [13, 14]. The Θ_p(T) curves were constructed at intervals of 10-15°C or sometimes only 2-3°C.

Figure 1a shows the concentration dependence a(c) of the lattice constant. There is a clear deviation from the Vegard law, as was pointed out in [15]. Figure 2 shows the temperature dependence of the lattice constant for these alloys; we see from the a(T) curve that the thermal expansion coefficient α is very nonlinear, implying higher-order anharmonic contributions and second-order phase transitions in the alloys rich in Ni. The thermal expansion coefficient of the lattice is also a nonlinear function of the concentration. Here we will not reproduce data on second-order phase transitions in the Cu–Ni system; we merely show dashed curves at the corresponding temperatures in the figures. Figure 3 shows the temperature dependence of the logarithm of the relative intensity lnI/I_0(T) (where I is the integral intensity for an interference peak of a given reflection at temperature T; and I_0 is the intensity of the same reflection at room temperature). In this figure the lnI/I_0(T) curves are seen to undergo a relative displacement. The lnI/I_0 data shown are the averages of the results of several measurements; the reproducibility was no worse than 5-6%. The nonlinearity of the lnI/I_0(T) curves correlates with that of the a(T) curves and can also be attributed to higher-order anharmonicity at the higher temperatures.

Figure 4 shows the Θ_p(T) dependence, while Fig. 1b shows the concentration dependence of Θ_p at room temperature. The experimental results show that Θ_p(c) is additive, as was pointed out in [16, 17]. The numerical values of Θ_p differ from those reported in [16, 17] for Ni-rich alloys, perhaps due to different procedures for analyzing the experimental data. The Θ_0 value for Ni (Θ_0 = 422°C) agrees well with...