SOVIET PHYSICS USPEKHI VOLUME 4, NUMBER 3 NOVEMBER-DECEMBER 1961

THE PHYSICAL PROPERTIES OF METALS OF HIGH PURITY

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Usp. Fiz. Nauk **74**, 31-60 (May, 1961)

1. INTRODUCTION

"PURE metals" always contain large amounts of various impurities, whose presence radically alters the properties of the metal, and sometimes even prevents its use for practical purposes. The efforts that are made to enhance the purity of certain metals have the purpose of improving their physical properties and making it possible to use them in those branches of modern technology; which impose a number of special demands on the properties of metals. On the other hand, the vigorous progress in methods for producing, purifying, and analyzing metals permits the use of extremely pure specimens in carrying out various physical investigations. In many cases high chemical purity of the material studied is a necessary condition for the work; this is the case, for example, in experimental work on the electronic state of a metal.

Clearly the general level of achievement in the field of the purification of metals is still not at all high. As the purity is improved, however, it is very often possible to detect marked changes in the physical properties of a metal. We have used the reports published in recent years on studies of metals of high purity. The Appendix presents some information about the studies of pure metals that have been made in the last few years; these show a general tendency toward increasing purity of the specimens, and also show that the results achieved in this direction are different for different metals. It must be noted, however, that the Appendix does not include papers on work in which the metals used were evidently very pure, but no data are given on the degree of purity of the specimens; it is stated, for example, that metals "of the highest purity" were studied, or the only indication given is data on the electric resistance. In some cases the last circumstance has been taken into account.

The present review does not include information about semiconductors, which are subjected to more careful purification than metals with ordinary electronic conductivity; the only problems considered are those in the physics of metals in whose study the purity of the specimens is a matter of primary concern.

The sensitivity to impurities of certain physical properties, for example, the effective cross section for capture of neutrons and other products of nuclear reactions, resistance to corrosion, and high-temperature stability, depends on the chemical composition. Other physical properties show little dependence on the chemical nature of the impurities. In particular, the electric resistance increases with increase of any kind of local disturbances due either to impurity atoms or to vacancies or other inhomogeneities of atomic scale. Finally, a broad class of structure-sensitive properties of crystals is affected by impurities only indirectly, through changes in the structures of cast or annealed specimens. As a rule, effects of impurities show up first in the structure of crystal grains and blocks in metals. This brings with it a change of the concentration of local defects, such as vacancies and interstitial atoms of the main metal, dislocations, and nets and walls of dislocations. Structure-sensitive properties include plasticity, creep, strength, slip elements, and so on. The list of physical properties considered in this review has been determined by the research reports now available in which one or several physical properties are correlated with the concentration of impurities in metals.

2. THE ELECTRIC RESISTANCE

As is well known, the electric resistance of a metal depends on the temperature and on the concentrations of impurities and local defects. The relative influence of the impurities and local defects increases strongly as the temperature is lowered. Usually the part played by vacancies is very small at low temperatures, since their equilibrium concentration at room temperature is 10^{-16} percent.[1] A crystal can, however, be supersaturated with vacancies as the result of cold working or quenching. At 1000° C the concentration of vacancies can be as much as 10^{-2} percent. If an appreciable fraction of the vacancies are fixed by quenching, their influence on the electric resistance at low temperatures becomes comparable with that of the usual impurities. In cases in which the object of investigation is the concentration of vacancies after quenching, annealing, or plastic deformation, one must have extremely pure specimens to be able to detect the change of the electric resistance associated with a change of the concentration of vacancies.

The residual electric resistance ρ_0 defined by Matthiessen's rule

$$\varrho = \varrho_0 + \varrho(T) \tag{1}$$

[where $\rho(T)$ is the resistance caused by the thermal vibrations] is the most important quantity characteristic of the concentration of impurity atoms, vacancies, and other local defects. Instead of ρ_0 one usually uses the ratio of the electric resistance at some low temperature (helium, hydrogen, or nitrogen temperature) to that at room temperature. The latter is assumed independent of the concentration of impurities.

It has turned out that the temperature dependence of the electric resistance is more complicated than that described by Eq. (1). In many cases the existence of a minimum of the electric resistance is noted.[2-5] It is supposed that this phenomenon can be explained by the effect of a small number of paramagnetic ions dissolved in the lattice of the metal. Evidently the effect is due to a peculiarity of the scattering of the conduction electrons by the paramagnetic impurity.[6]

In some cases the appearance of a minimum is due to the uncontrolled introduction of contaminations. For example, L. S. Kan and B. G. Lazarev[2] have shown that in magnesium the appearance of a minimum in the temperature dependence of the resistance was explained by contaminations which had been introduced into the specimens in the process of attaching the current-carrying and potentiometer leads.

V. B. Zernov and Yu. V. Sharvin[7] have used a method without contacts to study the electric resistance of tin at low temperatures. In the range of temperatures from that of liquid helium (4.2° K) to the transition point into the superconducting state (3.73° K) the resistance of a single crystal of tin was reduced one half. In this range there is good agreement with the relation

$$\bar{\varrho} = \bar{\varrho}_0 + \bar{b}T^5. \tag{2}$$

The writers take the quantity $\bar{\rho}_0$ in Eq. (2) as the residual resistance, which satisfies the relation

$$C = 20\frac{\bar{\varrho}_0}{\varrho_{20^\circ\,\mathrm{C}}}\,\%, \tag{3}$$

where C is the concentration of all the impurities, independent of their nature. By all appearances, specimens of tin of the highest purity were produced in this work. The starting material was tin with 0.1 percent impurities. Two successive processes of electrolysis, heating to incandescence in vacuum at 1200 — 1400° C, and 166 zone meltings gave a single crystal for which the relation (3) gives a purity of 99.99994 percent. Judging from the data on the electric resistance, tin of similar purity had been produced earlier by B. N. Aleksandrov and B. I. Verkin.[8] Tin may be the most suitable object for these methods of purification, since it combines a low melting point with a very high boiling point and low vapor pressure, which make for great effectiveness of vacuum-distillation processes.

If one takes the temperature dependence of the electric resistance into account in the proper way one can use the low-temperature resistance to trace changes in the total concentration of impurities, vacancies, dislocations, and other local defects.

Table I shows some data on the low-temperature resistance of metals of high purity. It follows from this table that for metals the ratio $\rho_{4.2^\circ\mathrm{K}}/\rho_{\mathrm{room}}$ is a quantity of the order of 10^{-3}. For very pure metals this ratio is diminished to 10^{-5} (tin, items 27 and 28).

The effects of structure and heat treatment can be characterized by the rule that the residual electric resistance increases as we go through the succession: single crystal, polycrystalline specimen, quenched specimen, plastically deformed specimen. The fact that the electric resistance is sensitive to the structure of the specimen is illustrated by many studies of a particular metal in different states. It is interesting to note that even the domain structure of a ferromagnetic specimen has a marked effect on its electric resistance. According to measurements made by A. I. Sudorov and E. E. Semenenko,[18] the resistance of specimens of high-purity iron is decreased by 25 percent when the domain structure is eliminated by the action of a weak external magnetic field.

3. THE REFLECTING POWER OF METALS

Many authors have studied the reflecting power of metals, both for the purpose of choosing materials for reflectors and in order to investigate the properties of the conduction electrons. Purification of aluminum makes it possible to obtain a material of extremely high reflecting power; for aluminum of purity 99 percent the reflecting power is 65 percent, and for 99.99 percent purity it rises to 84 percent. As is well known, as a material for reflectors aluminum has an advantage over silver, whose reflection coefficient drops sharply in the wavelength region near 3000 A. Alloys based on 99.99 percent pure aluminum have high reflecting power, and after being anodized are used as the material for reflectors, decorative details, and so on.

The basic experimental methods and the main results of modern studies in the optics of metals are described in the review by Schulz.[28] This review gives no attention to the effect of impurities on the optical properties of metals, but in its conclusion there is mention of the need for more careful experimental study of specimens of the best quality.

Also from the review articles devoted to the properties of the electrons in metals, for example those by I. M. Lifshitz and M. I. Kaganov[29] and by B. Lax,[30] one sees that almost all experimental studies of the electronic state of metals have to be made with specimens of high purity, in which the mean free path is shortened as little as possible by impurities.

4. THE MAGNETIC PERMEABILITY

It is well known that as the concentration of impurities in a ferromagnetic material is lowered the permeability increases and the coercive force decreases. Maykuth,[31] for example, states that an increase of the concentration of carbon from 0.002 to 0.004 percent

Table I. Some data on the residual electric resistance of metals of high purity

Content of pure metal, percent by weight, from analysis or found as difference	$(\rho_{T_1}/\rho_{T_2})\cdot 10^3$ $T_1 = 4.2°K$ T_2 = room temperature	Heat treatment	Literature reference, remarks
1. Aluminum–?	1.60	Anneal	9
2. Aluminum–99.995	86.0	Anneal	10; $T_1 = 78°K$
3. Aluminum–99.995	93.0	Quenching from 600°C	
4. Aluminum–?	0.43		11
5. Barium–?	7.87		12
6. Beryllium–?	11.0		13; single crystal
7. Bismuth–?	3.0		14; single crystal
8. Bismuth–99.998	6.2		15; single crystal
9. Tungsten–?	0.347		16; single crystal
10. Gallium–?	1.0	Anneal	17
11. Iron–99.996	4.0	Sublimation	18; iron content from data of B. G. Lazarev; with domain structure taken into account, $\rho_{4.2}/\rho_{\text{room}} = 3.0$
12. Gold–99.99	3.5	Anneal	19
13. Gold–99.9999	< 0.6		20; single crystal
14. Indium–?	1.71		9; single crystal
15. Indium–?	0.08		11; single crystal
16. Cadmium–?	0.5		21; single crystal
17. Cadmium–?	0.29		9; single crystal
18. Magnesium–99.99	~1.0		22; single crystal
19. Magnesium–?	4.57	No anneal	2
20. Magnesium–?	2.57	Anneal	9
21. Magnesium–?	2.24	Anneal	
22. Copper–99.999	2.5	Anneal	23
23. Copper–?	2.4	Anneal	9
24. Copper–?	6.41	Anneal	
25. Tin–99.994	0.4		24; single crystal
26. Tin–?	0.27		25; single crystal
27. Tin–?	0.018	Anneal	8
28. Tin–99.99994	0.010		7; single crystal
29. Platinum–?	2.0	Anneal	26
30. Zinc–?	0.57		26; single crystal
31. Zinc–?	0.47		27; single crystal

causes a lowering of the maximum value of the magnetic permeability ($\mu_{\max}$) of iron by a factor four. Further increase of the concentration of carbon already has a much smaller effect. The general nature of the dependence of $\mu_{\max}$ on the concentration of carbon is shown in Fig. 1. Some data on quantities characteristic of the magnetic properties of iron of various degrees of purity are presented in Table II. For comparison the table includes the values for an alloy of iron with 3.13 percent silicon (No. 8). With respect to $\mu_{\max}$ all of the specimens of pure iron processed in vacuum have the advantage as compared with the silicon iron. Technical types of iron have lower values. The highest value of the maximum permeability is that for the single crystal. Figure 2 shows the dependence of $\mu_{\max}$ on the concentration of carbon for silicon iron and for pure iron; it can be seen that a small amount of carbon has a large effect on $\mu_{\max}$ in all cases, but an increase of the carbon concentration has a greater effect on the properties of pure iron than on those of silicon iron.

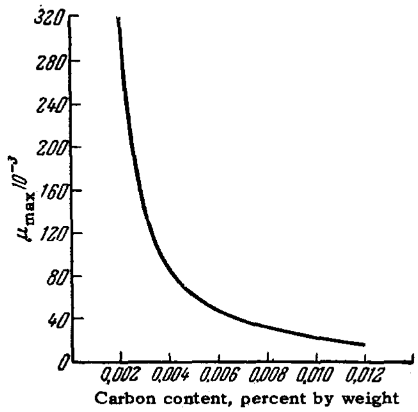


FIG. 1. Effect of carbon on the maximum magnetic permeability of iron.[31]

5. NUCLEAR REACTIONS

The demands made by atomic technology on the purity of materials are very severe, and are based on the great difference between the effective cross sections of various elements for particular nuclear reactions.

Table II. Magnetic properties of iron

Material (and literature reference)	Purity, weight percent (found as difference)	Number of impurity elements	μ_i	μ_{max}	H_c, oe	W_h, $\frac{\text{erg cm}^{-3}}{\text{cycle}}$
1. Electrolytic[32]	99,98	6	$2.5 \cdot 10^2$	$2 \cdot 10^4$	3—20	—
2. Cast in vacuum[32]	99,99	5	—	$2.07 \cdot 10^5$	0.0278	$0.7 \cdot 10^2$
3. Annealed in vacuum[32]	99,97	6	$1.4 \cdot 10^4$	$2,8 \cdot 10^5$	—	$1,9 \cdot 10^2$
4. Single crystal, annealed in vacuum[32]	99,98	6	—	$1.43 \cdot 10^6$	0,15	—
5. Armco iron[32]	99,94	5	$\sim 10^3$	$5 \cdot 10^3$	0.9	$\sim 6 \cdot 10^2$
6. Swedish iron[32]	99,85	5	—	$2,5 \cdot 10^3$	1,0	$\sim 3 \cdot 10^3$
7. Unalloyed steel[32]	99,63	5	$2,5 \cdot 10^2$	$5.5 \cdot 10^2$	—	$\sim 3 \cdot 10^3$
8. Silicon iron*[32]	99,82**	7***	$1,5 \cdot 10^3$	$4.7 \cdot 10^4$	0,6	$4,4 \cdot 10^2$
9. Bureau of Standards, USA[31]	99,9985	?	—	$3.2 \cdot 10^5$	—	—

Note: μ_i and μ_{max} are the initial and maximum values of the magnetic permeability; W_h is the loss per cycle at 50 cps and $B_{max} = 10^4$ gauss.

*Silicon 3.13 percent.

**With silicon.

***Without silicon.

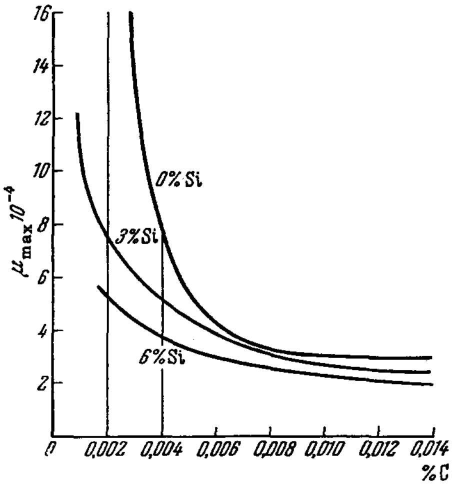


FIG. 2. Dependence of the maximum magnetic permeability on the concentration of carbon for iron and for alloys of iron with silicon.

The development of a pure-metal industry and of methods for purification are partly due to problems of atomic technology, reactor construction, and nuclear research. At a certain stage in the development of atomic reactors the possibility of achieving a chain reaction depended on the degree of purity of the materials with respect to elements having large cross sections for neutron capture.

Table III gives data on neutron capture cross sections, which show that the effects of the presence of the same amount of different elements as impurity will differ by factors of tens and hundreds of thousands.

According to the data of Holden[33] the purity of the uranium that is used can be characterized by the total amount present of 53 elements, amounting to 0.041 percent by weight. The precision of the determination of the concentration of each impurity element is 10^{-5} percent.

Table III. Neutron capture cross sections of certain metals (in barns)

Be—$9 \cdot 10^{-3}$	Fe—2.4	W—19,0
Mg—$5 \cdot 10^2$	Cr—2,9	Ta—21,0
Zr—0,18	Cu—3,6	Co—35,0
Al—0,22	Ni—4,5	Ag—60,0
Sn—0,65	V—4,7	Au—94,0
Zn—1,1	Ti—5,6	Hf—115,0
Nb—1,1	Mn—13,0	Cd—3500

A. S. Zaĭmovskii and others[34] have studied the properties of uranium with a total impurity content of 0.03 percent.

In atomic reactors great attention is also given to the purity of structural metals and alloys that do not take part in the reaction. In this connection the purification of such metals as beryllium, aluminum, magnesium, zirconium, and others, is the object of special efforts. In particular, it is well known that the use of zirconium in reactor construction was possible only after ways were found to rid it of traces of hafnium. For many purposes the isotopic composition of metals is of extreme importance, but this question is beyond the scope of the present review.

6. EFFECTS OF RADIOACTIVE IRRADIATION

In connection with the development of nuclear reactor construction, a new field of study of the properties of metals has come into being; this is the study of the effects of intense irradiation. Not only technical materials are studied, but also metals of high purity; such investigations are very important for the elucidation of processes of the formation and elimination of vacancies and other point defects, which affect the electric resistance, the elastic moduli, the internal friction, and other physical properties of irradiated metals.

For example, the effects of neutron irradiation on the elastic modulus and internal friction have recently been studied for copper of purity 99.999 percent.[35,36] It was found that comparatively small doses of neutron irradiation lead to a considerable increase of the elastic modulus and a lowering of the damping decrement of the elastic vibrations. The modulus of elasticity of a single crystal of copper was increased by 9.5 percent after irradiation with a dose of 5×10^{17} neutrons/cm^2. The damping decrement was decreased by a factor three. In another case a fivefold decrease of the damping decrement with a small increase of the elastic modulus (by 1.5 percent) was observed after irradiation with a dose of 3×10^{15} neutrons/cm^2. The high chemical purity of the crystals in question means that we must seek the explanation of these effects in the interaction of the neutrons with the atoms of the main substance. It is supposed that collisions of neutrons with copper atoms lead to the production of vacancies and injection of some atoms into interstitial positions in the crystal lattice. If such point defects are produced in the immediate neighborhood of dislocations, the mobility of the latter is restricted, which leads to an increase of the microscopically measured elastic modulus and a very great decrease of the work done against forces of internal friction, especially at audio frequencies. As is well known, impurity atoms have a similar effect, and therefore similar studies with insufficiently pure specimens do not lead to such definite results. Copper of purity 99.999 percent has also been subjected to irradiation with 1 Mev electrons.[37] The experiment was done not only at room temperature, but also at the temperature of liquid nitrogen, at which the defects produced have small mobilities. An increase of the elastic modulus by 1 to 2 percent was found after irradiation with a dose of 10^{18} electrons/cm^2. Specimens that had had a small amount of cold working were more sensitive to small doses of radiation than annealed or thoroughly cold-worked specimens. This is in good agreement with the hypothesis that the interaction of dislocations with local defects leads to the observed changes of the elastic modulus and the internal friction.

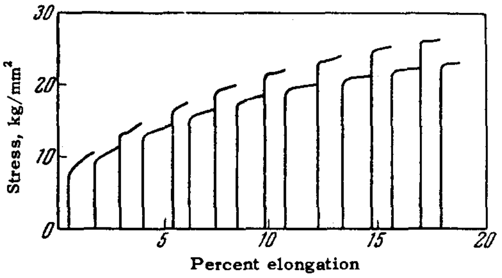


FIG. 3. "Stress-strain" curve of a nonirradiated polycrystalline copper specimen tested alternately at –195°C and 20°C.[38]

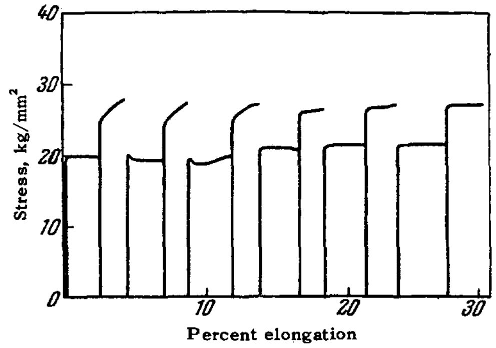


FIG. 4. "Stress-strain" curve of an irradiated polycrystalline copper specimen tested alternately at 20°C and –195°C.[38]

The mechanical loss of strength after irradiation in a reactor was studied for copper in which the total amount of 15 impurities was less than 1.48×10^{-2} percent.[38] Experimenting with single-crystal and polycrystalline specimens of such copper, Makin found that after irradiation in the reactor for 9 months at 100° C, to a total slow-neutron dose of 10^{20} neutrons/cm^2, the capacity of the copper for hardening under stretching is decidedly altered. Whereas for nonirradiated specimens alternate stretching at room temperature and at considerably lower temperatures leads as the deformation is increased to greater and greater differences in the flow limit, in specimens that have undergone irradiation one finds on the contrary a marked decrease of this difference (Figs. 3, 4). The obvious explanation of this effect is essentially that in the process of deformation at the higher temperature dislocations are released from the clouds of local defects that have been produced in the irradiation of the specimen. In contaminated specimens this effect will obviously be masked by clouds of impurity atoms around the dislocations. We may suppose that with increasing purity of a metal the difference between the properties of irradiated and nonirradiated specimens must increase.

Nickel with 99.999 percent pure metal content has been used for an electron-microscope study of the defects that appear as the result of irradiation in a reactor.[39] Foils of thickness $0.1 - 0.2\,\mu$ were placed inside evacuated quartz capsules and subjected to irradiation in a reactor up to total doses of 10^{16} to 10^{19} neutrons/cm^2. The specimens were examined with a transmitted beam in the electron microscope before and after irradiation. With magnifications from 40 to 65 thousand one could not detect the formation of new lines or loops of dislocations by the irradiation, since in the very thin layers there was no development of sufficiently large stresses around the vacancies that were produced. A large number of loops of dislocations are produced, however, when specimens 0.1 mm thick are irradiated with a dose of 10^{19} neutrons/cm^2 and then deformed by 2 percent and electrolytically etched to a depth of $\sim 0.1\,\mu$. Without irradiation these dislocations are not formed. Thus in the tests with very pure nickel it was clearly shown that during irradiation clouds of vacancies accumulate, which in the process of deformation form small disks of vacancies, and after the collapse of the disks there are loops of new dislocations of diameter about 50 A.

It is known that after irradiation metals become harder, the flow limit is higher, and the cold-embrittlement temperature is higher. During the process of irradiation, however, with the continuous production of new local defects the changes can be of a somewhat different kind. Therefore the problem of the change of the mechanical properties of metals as they undergo irradiation is an extremely important one. It has recently been found that under the influence of neutron irradiation the rate of creep of uranium is increased by a factor of 50 to 100.

The creep of other metals is not very sensitive to irradiation. The data of different authors are collected in Table IV; these data are remarkably contradictory. To explain the differences one can suppose that the rate of creep is determined by conditions at the boundaries of grains and blocks and that the metals tested by the various authors differed greatly in the distribu-

Table IV. Effect of irradiation on the creep of metals

Character of specimens			Radiation			Creep Test					
Material	Purity, percent	Dimension, mm	Type	Source	Intensity, particles/cm^2 sec	Temperature, °C	Duration	Load, kg/cm^2	Preliminary treatment	Result	Reference
1. Cadmium single crystal	?	0.04	α	Polonium	$1.5 \cdot 10^{18}$	Room	?	?	None	Acceleration	40
2. Cadmium single crystal	99.99 99.96	?	α	”	$5 \cdot 10^{18}$	Room	0–25 min	?	Various	No effect	41
3. Aluminum	?	Diam. 0.25	α	”	$5 \cdot 10^{18}$	200 ± 1	0–180 min	20.5	15 min anneal at 357°C	Slowing(?)	42
4. Aluminum	99.99	Diam. 0.346	α	Accelerator	$2.4 \cdot 10^{13}$	291–358	0.417 min	64	Anneal 340°C, *10 min* heating	Slowing(?)	42
5. Aluminum	99.35	0.4–0.1 length 125	α	”	$1.2 \cdot 10^{13}$	163–325	30–40 min	?	None	Slowing(?)	42
6. Aluminum	?	?	?	Cyclotron	?	?	?		?	No effect	43
7. Aluminum	?	Tube 50×0.05 length 375	n	Reactor	$1.3 \cdot 10^{12}$ fast, $6 \cdot 10^{12}$ thermal	50	0–600 hr	?	None	Acceleration	44
8. Aluminum	?	?	n	”	$8 \cdot 10^{11}$, 0.6 Mev	350	?	62.6	?	Slowing(?)	43
9. Copper	99.98	Diam. 0.5	d	?	10^{12}	260	10–50 hr	?	Anneal in vacuum 1 hr at 300°C	No effect	45
10. Nickel	?	?	n	Reactor	$3 \cdot 10^{11}$	700	?	?	?	Slight change	43
11. Nickel	?	?	n	”	$6 \cdot 10^{12}$	500	?	?	?	No change	43
12. Zirconium	?	?	n	”	$3 \cdot 10^{12}$ above 0.5 Mev	649–760	?	1090–2530	?	Slowing	43
13. Stainless steel	–	?	n	”	$3 \cdot 10^{11}$ above 0.5 Mev	260	?	?	Bending	Slowing	43
14. Niconel	–	?	n	”	$5 \cdot 10^{12}$ above 0.1 Mev	705	?	?	?	Slight change	43
15. Constantan	–	?	n	”	$3 \cdot 10^{12}$	300	?	1270	?	No effect	43
16. Zinc single crystal	99.995	0.3 and 0.1 diam.	α	Polonium	$(4.3–6.3) \cdot 10^{8}$	Room	0–60 sec	9.8–21.6	Aging at room temperature and etching	Slowing	46
17. Zinc single crystal	99.995	?	n	Radon-beryllium	?	Room	0–60 sec	14	None	Acceleration	46
18. Zinc single crystal	99.995	0.4–0.5	β	P^{32}	$(2.8–3.7)$ 10^{9}	Room	0–60 sec	20.5–24.0	None	Acceleration	46
19. Polycrystalline uranium	99.97	2.0 diam.	n	Reactor	6.10^{12}	220	300 hr	Up to 15.8	Anneal, quench, rolling, recrystallization	Acceleration by factor 50–100	47

tion and nature of the impurities they contained. It is obvious that volume diffusion did not determine the rate of creep in all of these cases, because small variations in composition could not lead to such great changes in the character of the effect of the impurities on the creep rate under irradiation.

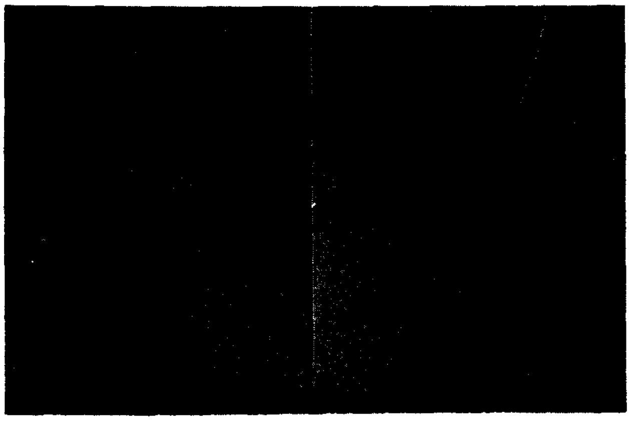
The question of the effect of irradiation on the rate of creep was first raised in a note by Andrade,[40] who found an acceleration of creep in cadmium single crystals as a result of irradiation of the surface with α particles from a weak polonium source. It is important to point out that the intensity of the radiation and the depth of its penetration were so slight that to this day the existence of such an effect is surprising. An attempt to reproduce this experiment with more intense irradiation, which was undertaken in 1955,[41] led to negative results. Nevertheless, as has been stated, the similar effect in uranium is very large. As is seen from the data of Table IV, it is also observed in aluminum[44] and zinc.[46] In some cases irradiation leads to a lowering of the rate of creep, which is easily explained by the blocking of dislocations at the defects produced by the radiation.

7. BOUNDARIES BETWEEN MICROSCOPIC CRYSTALS

Grain boundaries are usually especially rich in impurities. In nickel of purity 99.99 percent, however, it has evidently been possible to obtain direct contact between the grains without an appreciable intermediate layer. In this case it was found that etching figures showed localized stresses, which can be regarded as the result of lack of crystal-geometrical correspondence between the grain faces that were in contact.[48]

With contamination of the boundaries in polycrystalline iron the same author observed the appearance of a dense system of similar defects localized right at the boundary.

Figure 5 shows a photograph of the etching figures of two large grains in nickel (a and b), in which the traces of local strains can be seen easily.



a) b)

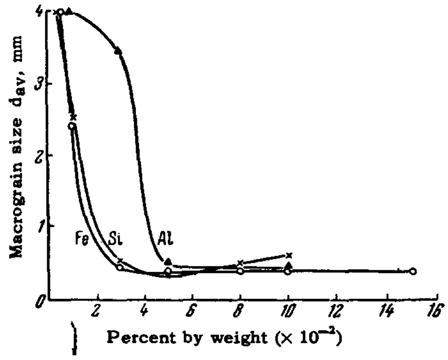
FIG. 5. Local distortions at grain boundaries in nickel, as brought out by etching[48] (×350).

If a metal is contaminated with oxygen, for example, then such stressed regions are more uniformly distributed along all of the grain boundaries and give the impression of a dislocation structure of the boundary. It must be mentioned that some authors incline to the view that etching does not bring out all of the dislocations, but only those that are decorated with impurities. On the other hand there are many grounds for thinking that local stresses are necessarily revealed by etching, independently of the presence of dislocations. Therefore it is easy to agree with the opinion of the author of reference 48, that impurities localized on grain boundaries of themselves (without dislocations) produce stresses which are responsible for the appearance of a specific etching figure of the grain boundaries.

In the measurement of the surface energy of the boundaries between microscopic crystals the purity of the metal is of exceptionally great importance. One such measurement has been made for zinc by Aström,[49] who observed with a calorimeter the development of heat during selective recrystallization and found that the surface energy of the grain boundaries in zinc is 1720 — 1920 erg/cm^2. Unfortunately, Aström did his experiments with relatively impure metal, containing 0.11 percent by weight of iron and lead alone. Therefore it is hard to accept his data as characteristic of zinc.

It is well known that a rise in the concentration of impurities leads to a decrease of grain size. For example, in reference 34 the relation between grain size and impurity concentration was found, as shown in Fig. 6.

FIG. 6. Effect of impurities on grain size in uranium.[34]



8. THE LATENT ENERGY OF PLASTIC DEFORMATION. RELAXATION AND RECRYSTALLIZATION

The unequal effects of various impurities on the recrystallization transformation of grains has recently been studied in a paper by Blade,[50] who showed that in aluminum of initial purity 99.998 percent some impurities (Ge, Ag, Zn, Si, Cu) caused an acceleration of the formation and growth of new grains, and others (Fe, W), on the contrary, made these processes go more slowly. Manganese and silver had no appreci-

Table V. Latent energy of plastic deformation

Material	Pure metal content, percent by weight	Deformation	(Q_p/Q_0)*	Reference
1. Copper	99.999	Stretching by 10–40 percent	From 10 to 30	51
2. Copper	99.988	Twist (nd/l)** from 0.5 to 3	~ 20	52
3. Copper	99.967	Twist (nd/l)** from 0.5 to 3	~ 3	
4. Copper	99.98	Compression by 10–70 percent	>30	53
5. Copper	?	Rolling, reduction $\psi = 25$ percent†	~ 10	54
6. Copper	?	Cyclic stretch and compression to fracture: $\sigma = 7$ kg/mm², $N = 10^6$.††	~ 0	54
7. Copper	?	Bending back and forth to fracture; $\sigma = 18$ kg/mm², $N = 2.8 \times 10^5$	~ 1	54
8. Copper	?	Rolling, $\psi = 25$ percent, then bending back and forth to fracture; $\sigma = 15$ kg/mm², $N = 5 \times 10^5$	~ 5	54
9. Copper	?	Rolling to doubled length	~ 0	55
10. Copper	99.96	Compression by 5–55 percent	~ 0	56
11. Copper	99.8	Compression by 40–70 percent	<0.1	57
12. Copper	?	Forging at temperatures from 0°C to 30°C, $\psi = 85$ percent	~ 0	51
13. Nickel	99.6	Twist $(nd/l) = 0.94$	~ 3	54
14. Nickel	99.6	Cyclic stretch and compression to fracture; $\sigma = 7$ kg/mm², $N = 10^6$	~ 1	54
15. Nickel	99.6	The same without fracture, $N = 5 \times 10^5$	~ 1	54

*Q_p is the part of the latent energy of deformation that is released in the recrystallization; $Q_0 = Q - Q_p$, where Q is the entire latent energy released in annealing.

**n is the number of turns, d the diameter, and l the length of the specimen.

†ψ is the fractional decrease of the cross sectional area.

††σ is the stress, and N is the number of cycles.

able effect on the rate of recrystallization at concentrations up to 0.04 percent.

The question of the influence of impurities on recrystallization has another and somewhat different aspect if we take into account the fact that recrystallization is usually activated by a preliminary plastic deformation. The nature of the defects produced by plastic deformation depends on the purity of the metal, on the maximum stresses and strains, and to a lesser degree on the type of deformation. It has been found that the latent energy of deformation distributes itself in different ways between the energy of local defects such as vacancies and the like, and distortions that are eliminated in recrystallization. We present below data on the distribution of the latent energy of deformation.

The total amount of latent energy of deformation may possibly depend on the purity of the metal, but, because of the fact that in a given case the experiments of different authors generally give decidedly different results, one cannot determine the effect of purity on the capacity of a metal to accumulate latent energy in plastic deformation. On the other hand, studies of the process of release of latent energy of deformation during annealing enable us to compare the energy of dispersed defects (Q_0) with the energy released in recrystallization (Q_p). Table V gives a collection of such results, from which we can conclude that at higher purities a larger part of the latent energy is released in recrystallization. Local defects, which are eliminated in the process of low-temperature annealing, accumulate in larger numbers in more impure metals. Figure 7 shows the temperature dependence of the hardness and the amount of energy of plastic deformation released in annealing for very pure copper. Figure 8 shows similar data for nickel with a larger amount of impurities (99.6 percent pure). Curves a and c are the hardness. The curves b refer to the relase of energy for specimens worked by

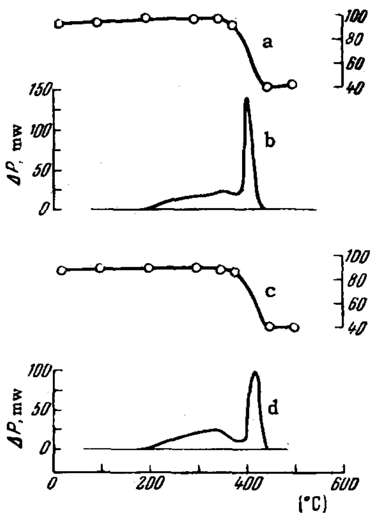


FIG. 7. Curves of change of hardness (a and c) and of release of latent energy (b and d) in annealing of plastically deformed copper.[54]

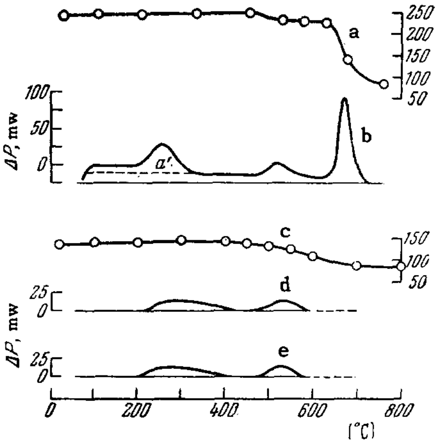


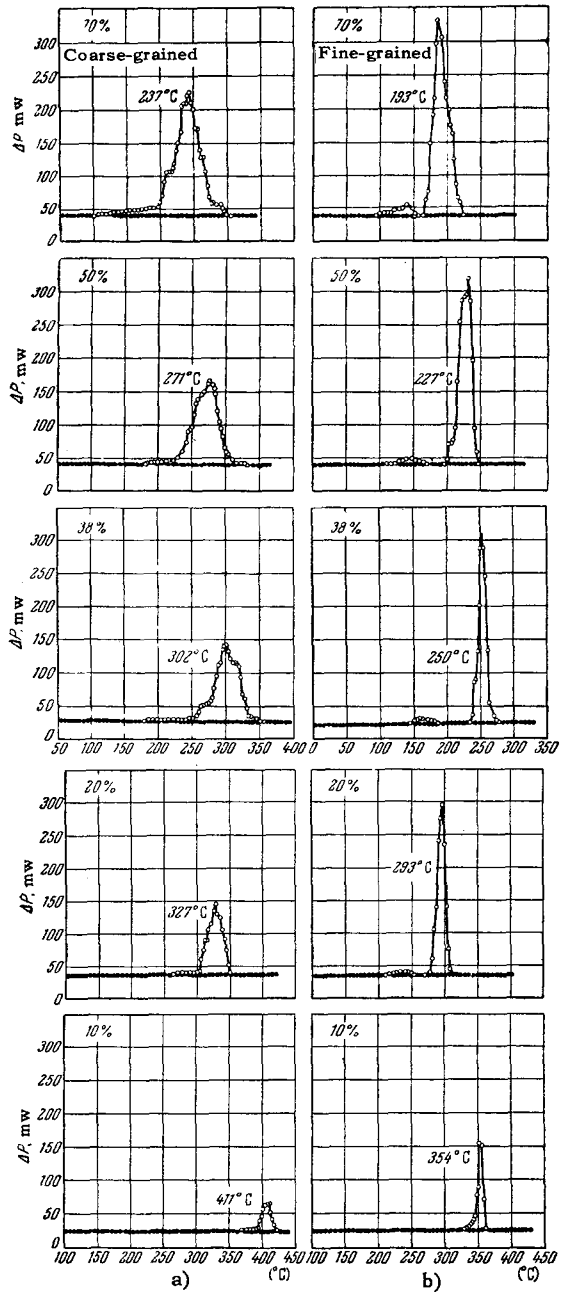
FIG. 8. Curves of change of hardness (a and c) and of release of latent energy (b, d, and e) in annealing of plastically deformed nickel. Purity 99.6 percent.[54]

twisting. Curve d in Fig. 7 is for twisting with subsequent fatigue test. Curves d and e in Fig. 8 are fatigue tests.

Figure 9 shows data from the results of annealing coarse-grained and fine-grained copper after various amounts of deformation. The regions of Q_p and Q_0 become better separated with increase of the degree of deformation and decrease of the grain size. In particular it can be seen from Fig. 8 and Table V that fatigue tests are affected mainly by the accumulation of local defects, which are evidently generated in overstressed regions. These processes do not lead to damage to the main mass of the metal. Otherwise fatigue testing would cause a considerable increase of Q_p, whereas actually fatigue testing results in an increase of Q_0 and has almost no effect on Q_p.

It is interesting to note that according to measurements made by Gordon[51] the activation energy of the recrystallization process does not depend on the magnitude of the deformation. This important observation can be the basis for the view that for large degrees of forging the process of plastic deformation consists in the breaking up of the blocks of the mosaic, with the appearance of new surfaces, but with the coherence blocks themselves remaining undistorted.[58] Relating to this we have the arguments of M. Ya. Gal'perin, E. P. Kostyukova, and B. M. Rovinskii,[59] who showed that in plastic deformation of aluminum and nickel along with the breaking up of blocks there is restoration of large coherence blocks. These authors believe that a recrystallization process is occurring. The data presented in Figs. 7 and 8 can be regarded as a confirmation of the conclusions of Rovinskii et al.

The formation of blocks in recrystallization shows a direct dependence on the concentration of impurities and the rate of growth of crystals, as has been shown by D. E. Ovsienko and E. I. Sosina in the case of crystals of aluminum with copper and zinc added as impurities.[60] Obviously the problem of the nature of processes of plastic deformation, which is closely connected with the breaking up of blocks and the restoration of contacts, must be studied with extremely pure metals, in order to exclude the complicating effects of impurities. On the other hand, impurities and alloying substances can decidely alter the mechanical properties of a metal, since the presence of impurities leads to breaking up of the blocks (alloy hardening). In such alloys plastic deformation leads only to displacement of the blocks, which are small enough not to be broken up under the action of the stresses.



a) b)

FIG. 9. Curves of release of latent energy in annealing of plastic deformation of coarse-grained (a) and fine-grained (b) copper. Purity 99.98 percent.[53] Average diameter of coarse grains 0.15 mm, of fine grains 0.03 mm. Degrees of compression: 10, 20, 38, 50, and 70 percent.

9. INTERNAL FRICTION AND MODULI OF ELASTICITY

Many studies give reason to think that the elastic moduli are not sensitive to small amounts of impurities and contaminations. The internal friction, on the other hand, can in many cases be the most sensitive indicator of the presence of small amounts of impurity. It is important to note that whereas the residual resistance can be used to characterize the total amount of impurities, in many cases the method of internal friction permits discriminations. This method has been successfully used to study the effect of neutron irradiation of 99.999 percent pure copper (see references 35, 36), the effect of the superconductive transition in tin of purity 99.9987 percent (reference 61), of plastic deformation in 99.99 percent pure cadmium (reference 62), of deformation and alloying in 99.99 percent pure aluminum (references 63, 64), and of purification of iron to 99.99 percent (reference 65).

The effect of impurities on the internal friction of metals has been the object of special study in papers by many authors. Snoek[66] was probably the first to use the method of the damping of mechanical vibrations to study the properties of impurities dissolved in metals. He studied α iron containing various (extremely small) amounts of nitrogen and carbon, and observed the presence of a maximum in the curve of the temperature dependence of the internal friction, which disappeared in cases in which it could be supposed that the specimen contained no appreciable amount of these impurities in solution. The saturation was carried out at 600° C in an atmosphere of hydrogen with a small amount of ammonia, and the measurement of the decrement was made with torsional vibrations in the temperature range from $-50°$ to $+70°$ C, with a vibration period of 4.9 sec. The solubility of carbon in α iron at room temperature, determined by this method, was estimated as a quantity smaller than 10^{-4} percent. The solubility of nitrogen at 500 — 600° C turned out to be 6×10^{-2} percent.

Ke T'ing-Sui has studied solid solutions of carbon and oxygen in tantalum by the method of freely damped torsional vibrations and has shown that these impurities form solid solutions of the interstitial type.[67] The purity of the tantalum was 99.9 percent, the temperature range 20° to 400° C, and the oscillation frequencies were 0.31, 1.2, and 4.6 cps. The heat of activation for displacement of carbon dissolved in tantalum is 25 kcal/mole, and that for oxygen is 29 kcal/mole.

A more general treatment of the question of the action of mechanical stresses on atoms dissolved in a crystal lattice is given in a paper by Zener.[68]

In recent years much attention has been given to the study of peaks of the internal friction at audio frequencies, which are ascribed to properties of dislocations and their interaction with impurities. Niblett and Wilks[69] have studied the damping of elastic vibrations of 99.999 percent pure copper rods at frequency ~ 1100 cps in the temperature range from 20° to 200° C. It was found that at temperatures $\sim 40°$ C and 70° C there are peaks of the internal friction, whose heights are mainly determined by the previous deformation and do not depend on the presence of bismuth (2.6×10^{-3} percent) and phosphorus (3.2×10^{-3} percent) as impurities.

In discussing these results Seeger[70] came to the conclusion that in this case the internal friction is due to losses arising from the interaction of the stresses and the thermal motion with the dislocations.

In a study of 99.99 percent pure aluminum by a similar method (frequency $\sim 1200 - 1300$ cps) in the temperature range from room temperature to $-196°$ C, V. A. Pavlov found two maxima in the curve of the temperature dependence of the damping decrement of the vibrations.[64] The author believes it possible to ascribe the peak at $-50°$, $-80°$ C to the effect of processes of diffusive displacement of vacancies, and that at $-170°$, $-180°$ C to displacements of groups of vacancies. V. A. Pavlov regards the observed monotonic increase of the damping decrement as the temperature of liquid nitrogen is approached as due to diffusive displacement of interstitial atoms. The corresponding values of the activation energy are 0.5, 1.14, and 0.5 ev.

The influence of forging of steel on the damping of elastic vibrations has been studied by V. A. Zhuravlev.[72] It was found that at room temperature, for a frequency of about 300 cps, the decrement increases by a factor eight after stretching by 7 percent. There is a decided increase of the internal friction in the process of plastic deformation. For example, in 99.97 percent pure aluminum the ultrasonic absorption is approximately proportional to the rate of slip.[73]

It has also been found that within the elastic limit the observed increase of the damping decrement with increasing amounts of additional stress can be explained by processes of plastic deformation in microscopic regions of overstress.[74]

Figure 10 shows the time dependence of the total stress (curve 3) when a harmonic component and a linearly increasing component are superposed. The shaded regions correspond to conditions of active plastic deformation in microscopic regions of overstress. The work of this deformation increases with increase of the slope of the straight line 2, i.e., with the rate of increase of the additional stress. This leads to a definite increase of the damping decrement, which has been observed experimentally.[74]

10. MECHANICAL PROPERTIES

With the exception of the elastic modulus, all of the mechanical properties of metals are extremely sensitive to impurities and alloying.

Plasticity. The most important requirement imposed on the metals chosen for various fabrications is

Table VII

Temperature of test, °K	Purity of beryllium, percent by weight	Deformation before appearance of bands, percent	Yield point, kg/mm^2	Total residual compression, percent	Tensile strength, kg/mm^2
20	99.7	No slip bands observed		2.4	48.0
	99.98	2.0	14.0	8.8	37.0
77	99,7	3,0	42.0	6.0	52.0
	99.98	0,3	3,4	22,0	34,0

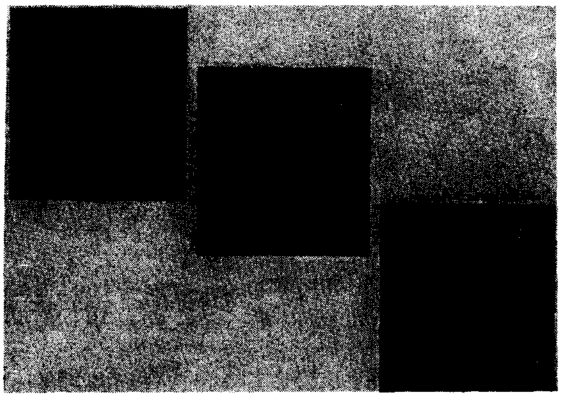


FIG. 16. Intergrain slip of coarse-grained iron at −269°C. The break in the microinterference bands at the boundary of the displaced grains increases with the distance from the place where three grains come together (the point O). Purity 99.99 percent[80] (×330).

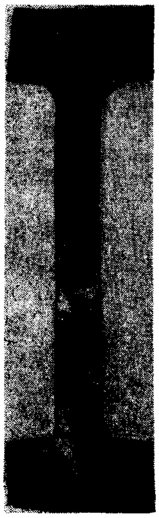


FIG. 17. External view of an iron specimen[80] stretched by 5 percent at −196°C. Purity 99.99 percent. Thick twinning layers can be seen[80] (×3.5).

there is considerable plastic deformation, which is mainly due to the formation and development of unusually thick twinning layers (of thicknesses up to 20 microns). Stepwise deformation has shown that in pure iron mechanical twinnings appear long before fracture and are found along the entire length of the specimen. A photograph of the external appearance of a specimen of pure iron with thick twinning layers is shown in Fig. 17.

In the deformation of pure iron in liquid nitrogen, simultaneously with the appearance of mechanical twinnings there is slip along their boundaries.[81] The shearing deformations localized at the twinning boundaries can be detected from the displacement of lines previously drawn on a ground section, and also from the break in the interference bands at these boundaries (Fig. 18).

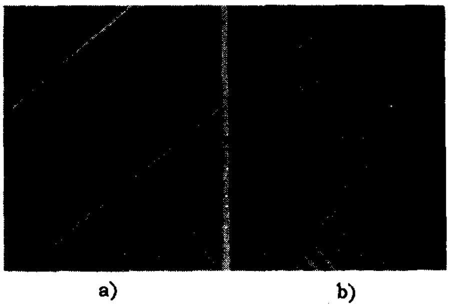


FIG. 18. Slip along the boundaries of twinning layers in iron. One can see the displacement of the line (a) and of the interference bands (b) at the upper surface of the lower twinning layer[81] (×440).

Mechanical twinnings are not formed in metals with the face-centered cubic lattice. Nevertheless low-temperature deformation of face-centered cubic metals of high purity is associated with the appearance of twinning layers. For example, stretching of 99.994 percent pure aluminum at 4.2° K leads to the formation of twinnings.[82]

In sufficiently pure metals, for example in 99.994 percent pure aluminum or 99.99 percent pure iron, deformation at helium temperatures is accompanied by mechanical recrystallization — the formation of large grains, of sizes exceeding those of the original grains of the metal. The mechanical recrystallization phenomenon is that under the action of stresses separate parts of crystal grains get reoriented and arranged to correspond to the orientation of adjacent grains. This phenomenon is similar to mechanical twinning in the presence of twinning layers and is accompanied by discontinuous shifts of boundaries between grains. The discontinuous (or spasmodic) character of the process is indicated by the presence of several successive positions of the grain boundaries, as revealed by stepwise deformation with intervening warming to room temperature.[83]

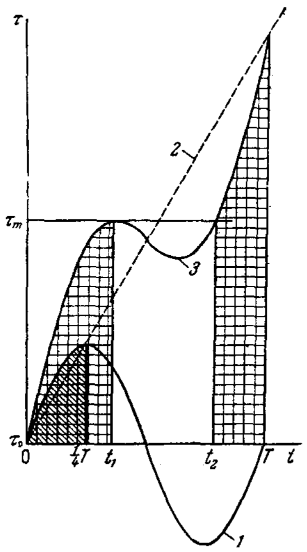


FIG. 10. The application of a linearly increasing stress in addition to the harmonically varying stress leads to an increase of the work of plastic deformation in microscopic regions of overstress. 1 – harmonic component of stress; 2 – linearly increasing stress; 3 – sum of stresses.[74]

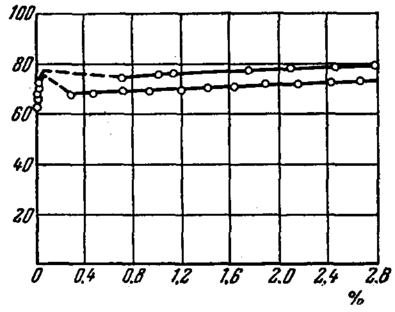


FIG. 11. Deformation curves for zinc: upper curve is for dynamic loading, lower curve for static loading.[76] Purity 99.99 percent.

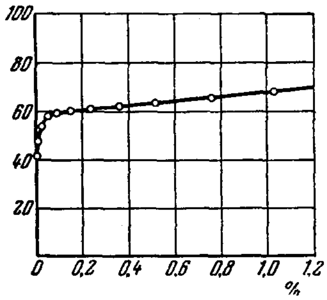


FIG. 12. Curve of static tension of zinc. Purity 99.999 percent.[76]

that of plasticity. Even now certain metals cannot be used as they should be because of their brittleness, in spite of a number of exceptionally important properties (for example, chromium resists heat and corrosion and is hard; beryllium has a small cross section for neutron capture, is light, and resists corrosion and heat). Other metals have come into use only after it became possible, as the result of the development of new methods of purification, to produce them with sufficient plasticity (for example, zirconium). Even such a plastic metal as aluminum becomes more plastic when it is carefully purified, and takes on other properties, such as high reflecting power and high resistance to corrosion.

It is stated by Maykuth[31] that aluminum of high purity is used to replace lead for pipes.

Recently, by means of the iodide process, Emel'yanov, Evstyukhin, Abonin, and Statsenko have produced chromium of purity 99.944 percent, which has considerable plasticity at room temperature[75] (see Table VI).

Deformation Curve. The shape of the deformation curve shows important changes with increasing purity of the metal. Figure 11 shows deformation curves for zinc of purity 99.99 percent, taken with dynamic loading (upper curve) and with static loading (lower curve); Fig. 12 shows the static deformation curve for zinc of purity 99.999 percent. A comparison of Figs. 11 and 12 shows that when we go from the less pure specimen to the purer one the yield point becomes much lower and the peak yield observed at small degrees of deformation is smoothed out.

In addition, the magnitude of the resistance modulus becomes less and less sensitive to the rate of deformation. Evidently the change from purity 99.99 percent to 99.999 percent zinc brings an elimination of Cottrell clouds and other obstacles to slip.

There are much more interesting differences between the deformation curves of impure and iodide chromium at room temperature,[75] which are shown in Fig. 13. Purification of the chromium leads to a sharp lowering of the flow limit and to a change from brittle to plastic fracture.

Cold Embrittlement. The threshold of cold embrittlement is defined as the temperature of the transition from the plastic type of fracture to the brittle type, and is very sensitive to impurities. The tests usually used to determine the cold-embrittlement temperature are static stretching or impulse bending. The former method gives much lower transition temperatures, and it is hard to correlate them with the data obtained from the resilience. With either method of determination, however, the cold-embrittlement temperature becomes lower with increasing purity. For example, the threshold of cold embrittlement of iodide chromium is lowered to – 15° to – 25° C. For coarse-grained iron of

Table VI. The mechanical properties of remelted iodide chromium

Dimensions of specimen before test			Dimensions of specimen after test			Yield point		Ultimate strength		Fractional elongation	Total decrease in cross section, percent
diameter, mm	length, mm	cross section, mm	diameter, mm	length, mm	cross section, mm	load, kg	stress, kg/mm²	load, kg	stress, kg/mm²	for length 5d, percent	
2.95	32.8	6.8	2.70	34.3	5.7	138	20.3	192	28.2	8.8	16.2
3.07	33.4	7.4	2.93	35.0	6.7	152	20.5	204	27.6	9.4	9.4
5.04	38.35	20	4.45	42.5	–	260	13.0	390	19.5	16.6	22.9

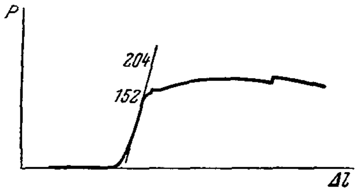


FIG. 13. Tension diagram of a specimen of cast iodide chromium.[75] Purity 99.944 percent.

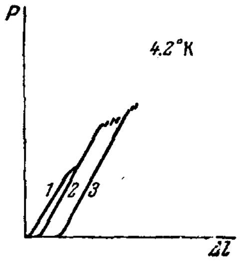


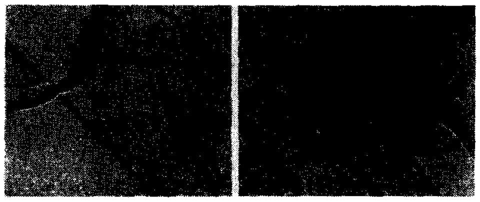
FIG. 14. Diagram of stepwise stretching of iron at 269°C, with warming to room temperature between loadings. Purity 99.99 percent.[77]

purity 99.99 percent the embrittlement temperature in tension is lower than 4.2° K. At this temperature there is appreciable plasticity, mainly owing to the formation and thickening of twinning layers. The above statements are well illustrated by the shape of the machine diagram (Fig. 14). The jumps in the curve $P = P(\Delta l)$ are due to mechanical twinning; the sections 2 and 3 of the curve correspond to repeated stretching in liquid helium after intermediate warming to room temperature. As can be seen, warming leads to a sharp increase of the flow limit in the subsequent low-temperature test, which is a consequence of thermal hardening of the boundaries of the twinning layers.[77]

Slip Traces, Twinning. The character of the slip traces is decidedly changed when the purity of a metal is increased. When there are impurities one observes nonuniform shear along separate slip bands; this effect can be a result of hindering of the slipping process along one plane and transition to slipping along a parallel plane at some distance. This can be regarded as the result of accumulation of dislocations at obstacles of the type of Cottrell clouds, or as a consequence of unequal strength of the contacts at different parts of the slip surface. The only reliable fact is that with increasing purity of the metal the uniformity of the shear along each slip band increases. It is interesting to compare[78,79] the basal slip traces in beryllium single crystals of different purities at low temperatures, which are shown in Fig. 15a (99.7 percent) and 15b (99.98 percent).

In commercial beryllium, basal slip is observed at 77° K in the form of thin, occasionally branching, closely spaced wavy lines; as the stress in increased the slip develops mainly through the formation of new thin bands. In the initial stages of the deformation there is nonuniform shear along an individual basal slip band, which causes the appearance of microscopic cracks along the planes of the prism and the pyramid of the second kind, and brings about the brittleness of beryllium at low temperatures.

In compression of specimens of pure beryllium slip



a) b)

FIG. 15. Traces of basal slip bands in single crystals of beryllium: a – compression by 3.4 percent at –196°C, purity 99.7 percent; b – compression by 5.2 percent at –196°C, purity 99.98 percent.[78,79]

along the (001) plane occurs already at 20° K and appears in the form of thin straight-line traces on the side faces of the specimen. Along with the single slip bands there occur slip packets with large relative displacement. Furthermore, for pure beryllium the flow limit is lower by more than a factor of ten. The low resistance to shear of single crystals of pure beryllium fits in with the weak development of the process of block formation in the initial state of deformation which precedes the appearance of the first slip bands. This in turn brings about the straight-line character of the slip trances in pure beryllium. For comparison Table VII shows the mechanical characteristics of beryllium crystals of different purities at 20° and 77° K.

As the purity of a metal is increased there is a change of the temperature range in which certain forms of plastic deformation occur. Besides this, special forms of plasticity appear, which are typical of extremely pure metals.

The conventional view is that intergrain slip can occur only at high temperatures under conditions of creep. It has been found, however, that this type of deformation is also observed at extremely low temperatures in the case of stretching of very pure iron at a comparatively high speed of stretch.[80] The slip along grain boundaries in 99.99 percent pure iron at temperature 4.2° K is shown in Fig. 16. After deformation an unetched ground section shows relief, and there is a break in the micro-interference bands at the boundary between the displaced grains. It is easy to believe that in the absence of impurities the properties of the boundaries between grains are comparable to those of other slip elements which run through the crystal. Evidently for extremely pure materials we cannot regard a deformation as consisting of quasiviscous and plastic parts, as is usually done for technical materials.

The removal of the impurities from a metal leads to a decided change in the process of appearance and development of twinning layers. At the temperature 77° K coarse-grained commercial iron undergoes brittle fracture; twinning layers are formed in such iron only at the instant of fracture and do not exceed one micron in thickness. In the stretching of specimens of 99.99 percent pure iron in liquid nitrogen

11. CONCLUSION

The study of the properties of metals of high purity has already yielded a number of new and important facts and results of practical use. The primary problems are obviously the study of the physical properties of materials of record purity and the search for ways to produce such materials.

There has as yet not been much light shed on the problem of the changes of the physical properties of metals when extremely small amounts of impurity are added. So far as the electric resistance is concerned, we can take as established the additivity of the effects of local defects from impurity atoms and from other causes, such as vacancies, etc. The mechanical properties are extremely sensitive to impurities, mainly on account of structural changes that arise during crystallization and other thermal processes. Vacancies and other local defects are obviously of less importance. The very important problem of removing the brittleness of a number of metals is at present being solved by methods for eliminating impurities. Further development of methods for the purification and analysis of specimens and for processing them will lead to the finding of new fields of application of very pure metals.

APPENDIX

Some Information on Studies of Metals of High Purity

Impurities			
number of elements determined	total amount present (percent by weight)	Purity of the metal (percent by weight)	Properties studied
		Aluminum	
–	–	99.9	Latent energy of deformation[57]
–	–	99.0 99.5 99.99	Plasticity, reflection of light[31]
–	–	99.99	Temperature and time dependences of strength[84]
4	$9 \cdot 10^{-3}$	–	Relaxation, recrystallization[85]
–	–	99.99	Recrystallization[86]
4	10^{-4}	–	Zone purification[87]
6	$3.4 \cdot 10^{-3}$	–	Slip, blocks, hardening[88]
4	$1.42 \cdot 10^{-2}$	–	Yield point, strength[89]
3	Traces	99.996	Effect of impurities on recrystallization[50]
–	–	99.99	Internal friction[63–64]
3	$2.2 \cdot 10^{-3}$	99.995	Energy of formation and motion of vacancies[10]
18	Traces of Cu	–	Energy of formation and motion of vacancies[90]
3	$4.2 \cdot 10^{-3}$	99.995	Block structure[60]
–	–	99.97	Ultrasonic absorption at different rates of creep[73]
–	–	99.996	Effect of ultrasonic waves on flow limit[91]
–	–	99.99	Reconstitution of blocks with cyclic loading[59]
–	–	99.99	Flow, creep, effect of impurities[92]
–	–	99.992	Peak of flow, unloading, aging[93]
–	–	99.994	Plasticity at low temperatures[82]
–	–	99.99	Slip, yield point of single crystals[94]
		Barium	
9	$3 \cdot 10^{-3}$	–	Purification[95]
		Beryllium	
10	0.132 without O_2	–	Casting in vacuum[96]
–	N_2	99.40	Powder metallurgy[97]
–	–	99.7	Slip and twinning of single crystals[98]
7	1.3	–	Impurities of commercial metal[99]
11	$0.6 \cdot 10^{-2}$	–	Sintering of powders[100]
11	10^{-2}	–	Refining; microhardness, plasticity of foils[101]
–	–	99.7	Slip and fracture of single crystals[76]
–	–	99.7	Microhardness of single crystals[102]
–	–	99.98	Slip of single crystals[79]
5	1.433	~98.5	Sharp peaks of internal friction[103]
		Vanadium	
5	$2 \cdot 10^{-2}$	99.9	Iodide refining[104]

APPENDIX (Cont'd)

Impurities			
number of elements determined	total amount present (percent by weight)	Purity of the metal (percent by weight)	Properties studied
Bismuth			
–	0.002	99.998	Galvanomagnetic properties[105]
–	0.04	–	Purification[106]
–	–	99.999	Semiconducting alloy with selenium[107]
–	–	99.99	Galvanomagnetic oscillations[108]
Tungsten			
3	0.056	–	Sagging on heating; additives which prevent sagging[109]
6	0.0525	–	Recrystallization[110]
Gallium			
–	–	99.9	Purification[111]
Hafnium			
11	0.958	~99	Iodide preparation, lattice parameters, density, polymorphism, melting, plasticity, recrystallization, oxidation, hardness, electric resistance[112]
Iron			
–	<0.0015	–	Plasticity, resistance to corrosion[31]
12	0.0385	–	Low-temperature plasticity of single crystals[113]
5	0.043	–	Effect of oxygen on mechanical aging[114]
10	0.011	–	Vacuum distillation[115]
10	0.0185	–	Internal friction and moduli[65]
–	–	99.99	Low-temperature fracture[80]
–	–	99.99	Thermal hardening of twinnings[77]
–	–	99.99	Slip along twinning boundaries[81]
Gold			
–	–	99.99	Energy of formation and displacement of vacancies[19]
–	–	99.998	Motion of vacancies and dislocations[116]
–	–	99.9999	Fermi surface[20]
Indium			
5	0.01	99.99	Purification[117]
Cadmium			
–	–	?	Acceleration of creep by α radiation[40]
–	–	99.96 and 99.99	No effect of acceleration of creep by α irradiation found[41]
–	–	99.99	Internal friction of forged polycrystalline and single-crystal specimens[62]
–	–	99.95	Effect of ultrasonic waves on flow limit[91]
Calcium			
6	$1.8 \cdot 10^{-2}$	–	Purification[95]
Cobalt			
–	0.3	–	Production of the pure metal[118]
Magnesium			
–	–	99.99	Residual resistance[2]
4	$1.4 \cdot 10^{-2}$	–	Purification[95]

APPENDIX (Cont'd)

Impurities		Purity of the metal (percent by weight)	Properties studied
number of elements determined	total amount present (percent by weight)		
Manganese			
9	$4\cdot10^{-2}$	–	Vacuum distillation[101]
Copper			
–	–	99.999	Recrystallization, latent energy of deformation[51]
–	–	99.98	Dependence of yield point and latent energy of deformation on size of crystal grains[53]
–	–	99.98	Latent energy of deformation and density[119]
10	0.92	99.98	Effect of impurities on residual resistance[23]
–	–	99.999	Effect of neutron irradiation on elastic modulus and internal friction[35,36]
–	–	99.999	Effect of electron irradiation on elastic modulus[37]
–	–	99.999	Annealing of radiation defects[120]
14	$1.43\cdot10^{-2}$	–	Mechanical weakening of irradiated copper[38]
8	$9.21\cdot10^{-4}$	–	Electrolytic separation of pure metal[121]
–	–	99.999	Internal friction, effect of plastic deformation[69]
Molybdenum			
16	0.16	–	Plasticity, welding[31]
?	?	?	Production of plastic metal[122]
Nickel			
–	–	99.99	Flow, relaxation[123]
–	–	99.99	Stresses near grain boundaries[48]
–	–	99.99	Effect of impurities on uniformity of distribution of slip traces[124]
–	–	99.99	Thermoelectric emf of deformed metal[125]
–	–	99.999	Radiation defects[139]
Niobium			
–	–	99.997	Structural distortions in various kinds of deformation[126]
Platinum			
–	–	99.92	Temperature and time dependence of strength[84]
–	–	>99.99	Galvanomagnetic phenomena[127]
–	–	>99.99	Energy of formation and displacement of vacancies[19]
Tin			
–	–	99.994	Galvanomagnetic phenomena[24]
6	$>1.3\cdot10^{-3}$	–	Elastic modulus and internal friction in the normal and superconducting states[61]
–	–	99.99994	Residual electric resistance[7]
Lead			
–	–	99.999	Fatigue[128]
4	$1.9\cdot10^{-3}$	>99.995	Elastic modulus and internal friction[61]
–	–	99.9999	Peak of flow after unloading, aging, recovery[93]
Silver			
–	–	99.95	Temperature and time dependence of strength[84]
–	–	99.99	Thermoelectric emf at contact with deformed metal[125]
–	–	99.999	Peak of flow[93]
Strontium			
10	$3\cdot10^{-2}$	–	Purification[95]

APPENDIX (Cont'd)

Impurities			
number of elements determined	total amount present (percent by weight)	Purity of the metal (percent by weight)	Properties studied
Antimony			
6	$<10^{-3}$	–	Zone purification[87]
Tantalum			
–	–	99.9	Solid solutions of carbon and oxygen. Internal friction[67]
Titanium			
–	–	99.9	Lattice parameters[129]
–	–	99.9	Thermal expansion[130]
–	–	99.95	Superconductivity[131]
8	1.42 atomic percent and iodide-process	–	Polymorphism[132,133]
11	0.3	–	Iodide purification[134]
Thorium			
12	0.48	99.50	Electrolytic preparation[135]
Uranium			
53	0.041	–	Metallurgy[33]
3	0.03	–	Polymorphism, grain, creep, hardness, strength, plasticity, effects of irradiation[34]
Chromium			
–	–	99.80	Lattice parameters[129]
20	0.066	–	Iodide purification, microscopic structure, hardness. Stretching, bending[75]
5	0.064	–	Alloy with iron[136]
13	0.0604	–	Vacuum distillation, microscopic hardness. Bending[137]
Zinc			
–	–	99.94	Temperature and time dependence of strength[84]
3	0.11	–	Energy of intergrain boundaries[49]
–	–	99.9985	Stretching of single crystals[138]
–	–	99.999	Stretching of single-crystal and three-crystal specimens[139]
–	–	99.99	Rate of twinning[140]
–	–	99.99 and 99.999	Basal slip[76]
–	–	99.999	Diffusion of vacancies[141]
–	–	99.995	Effect of ultrasonic waves on flow limit[91]
–	–	99.99	Brittle fracture of single crystals[142]
–	–	99.995	Effects of neutron and electron irradiation on the rate of creep of single crystals[46]
Zirconium			
–	–	99.9	Strength, plasticity, elastic modulus, neutron absorption[31]
16	<0.723	–	Electrolytic method of preparation, hardness, production of tubes[143]
20	<0.879	–	Oxidation[144]
12	<0.168	–	Oxidation of the metal and its alloys[71]

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