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Y-2126

**FACTORS AFFECTING THE DEFORMATION OF TUNGSTEN
(A Literature Survey)**

R. L. Ludwig

August 1978

**UNION
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**OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE**

*prepared for the U.S. DEPARTMENT OF ENERGY under
U.S. GOVERNMENT Contract W-7405 eng 26*

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$4.00 ; Microfiche \$3.00

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Date of Issue: August 25, 1978
Distribution Category: UC-25

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R. L. Ludwig

Metallurgy Department
Y-12 Development Division

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Prepared for the Department of Energy
Under US Government Contract W-7405-eng-26

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ABSTRACT

Background information relative to wrought tungsten forming was required in support of development studies. A summary has been made of pertinent information in *Metal Abstracts* from 1967 to mid 1977. Only a few papers were reviewed in their entirety; the great majority of information was derived from abstracts of the papers.

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SUMMARY

Background information relative to wrought tungsten forming was required in support of development studies. Seven principal areas of tungsten metallurgy were of interest: fabrication methods, delamination, recrystallization, heat treatment, fracture characteristics, impurity effects, and surface treatments. Pertinent information in *Metal Abstracts* from 1967 to mid 1977 was summarized for each area. Only a few papers were reviewed in their entirety; the great majority of information was derived from abstracts of the papers.

INTRODUCTION

One of the tasks of the Metallurgical Engineering Group of the Metallurgy Department, Oak Ridge Y-12 Plant^(a) Development Division, is to provide support for work directed toward developing the technology required for the forming of wrought tungsten parts. Of particular value in optimizing forming parameters is an understanding of those properties of tungsten which affect its deformability. This knowledge is also applicable when it becomes necessary to analyze the process by which a part may have failed in forming.

In addition, it is desirable to be aware of the manner in which tungsten responds to rolling and annealing so that the properties of the plate needed for forming may be specified. Impurities and small alloy additions may strongly affect the properties of tungsten so that knowledge in this area is important.

To provide a background of information covering the previously mentioned subjects, a search of the literature contained in *Metal Abstracts* from 1967 to mid 1977 was undertaken. With the exception of a few articles, only the abstracts were read. These sources were summarized in short writeups under the following seven topics: (1) fabrication methods used for tungsten; (2) delamination of worked tungsten; (3) recrystallization of tungsten; (4) heat treatment for optimizing the workability of tungsten; (5) fracture characteristics, brittleness, and the ductile/brittle transition temperature in tungsten; (6) effect of impurities and small alloy additions on the properties of tungsten, and (7) surface treatments and/or imposition of other conditions designed to augment ductility or reduce the cracking tendency of tungsten during working.

In each writeup, the contents of the various references are noted and are followed by a brief summary. A list of the references used appears at the end of the report.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the Department of Energy.

FACTORS AFFECTING TUNGSTEN DEFORMATION

LITERATURE SEARCH TOPICS

Fabrication Methods Used for Tungsten

References have been noted whereby various specific fabrication procedures have been adapted for use with tungsten. The process technology, principles, mathematics, applications, and practical data for flow turning a variety of metals and alloys have been reported.¹ The behavior of tungsten under stress in a very-high-pressure environment has been theorized and demonstrated. The stressed state arising in tungsten subjected to hydrostatic pressure was calculated and the maximum deformation which could be sustained without rupture was determined.² In an actual test, tungsten pulled under an environmental pressure in excess of 140 ksi (966 MPa) showed a reduction in area greater than 50%.³

Work has been done to demonstrate the explosive hot forming of certain steels and pure tungsten. Good hot formability was demonstrated for all of these materials.⁴ Tungsten sheet heated with infrared lamps has been bent, drop-hammer shaped, shallow drawn, sheared, and blanked.⁵

Tungsten has been solid-state welded without recrystallization. Precautions and pitfalls in the use of the techniques have been described.⁶

The literature has not yielded information of any value in the drawing of thick tungsten plate. It dealt primarily with thin sheet, which is more easily fabricated.

Delamination of Worked Tungsten

Tungsten, when rolled or forged, tends to develop a laminar structure which leaves planes of weakness in the worked material parallel to the plane of rolling. A Russian report discusses the structures produced in tungsten by rolling at 950° C and forging at 1200° C. It states that theory and experiment agree in revealing that, as well as a banded granular structure, a banded cellular structure is also created. The nonequiaxed granular structure may be adequately described on the basis of dislocation theory, while the nonequiaxed cellular structure arises both from polygonization and the lattice distortions attributable to rolling or forging. Cell boundaries in the worked metal usually lie in one plane; and this factor facilitates crack propagation.⁷ A second reference comments on the role of gaseous voids during deformation and fracture of tungsten. It is suggested that voids and inclusions lead to the development of internal strains that encourage lamination in certain conditions of excessive cold work.⁸ A note on cold-rolled molybdenum may be applicable to tungsten. It states that the layer-like structure with impurity-enriched grain boundaries in the rolling plane is probably responsible for the poor mechanical properties perpendicular to the rolling plane. Peculiarities of the rolling technique may also introduce a periodic structure.⁹

In a study on the fractography of tungsten and dilute tungsten-rhenium alloys, it was reported that wrought alloys tested in bending were more resistant to cleavage than recrystallized alloys, partly because failure by delamination prevented possible failure by cleavage. The mechanism of lamination was believed to be grain-boundary failure during rolling since the surfaces of delaminations were found to be entirely grain boundary. Therefore, the refining effect of rhenium on the as-cast grain size may significantly affect the number and width of laminations as well as the stage of rolling at which they first appear.¹⁰

Recrystallization of Tungsten

Rolled tungsten plate of powder origin purchased for forming experimentation has been observed to show unusual recrystallization behavior. Groups of large, recrystallized grains are observed to form at the mid-plate thickness location in contrast to the anticipated formation of a fine-grain structure throughout the plate. Various literature references have been found which may contribute to an understanding of this phenomenon.

A number of investigators have performed studies on the recrystallization of deformed tungsten single crystals of various orientations. High-purity, electron-beam zone-melted tungsten single crystals of (001) [110] orientation were deformed 70% by rolling at room temperature and 400° C. Mechanical properties and structure were observed as rolled and annealed (at temperatures to 3000° C). Recrystallization did not occur in any sample, but polygonization was detected. Annealed specimens were not brittle, but could be bent 180 degrees around a 3t radius.¹¹ In other work, tungsten single crystals of the same orientation, (001) [110], were rolled at 200° C. It was observed that recrystallization of the rolled tungsten always took place starting from the strip-edge region. The ratio of recrystallization temperature to melting point was very high for crystals rolled 60%.¹² A study of compressive deformation indicated that tungsten does not appear to recrystallize after compression along the [001] direction. The values of E_m , the critical compressive strain for crystal growth, are approximately 45 and 30% along the [011] and [111] axes, respectively.¹³ Single crystals of (111) $\bar{1}\bar{1}2$ orientation were deformed by rolling and recrystallized. Recrystallization took place with greater difficulty in the edge regions of the transverse sides of the specimens than in the central region.¹⁴

In a hardness study of tungsten single crystals, the anisotropy of deformation was demonstrated. Knoop microhardness values varied as the direction of the long axis of the Knoop indenter in the plane of the crystal was varied. Differences in hardness were pronounced on the {001} and {110} faces, but minor on the {111} faces.¹⁵

Work has been reported on structural changes taking place in tungsten single crystals that were subjected to various working and heat treatments. Crystals hot worked and annealed were studied by X-ray diffraction, microhardness, and residual electrical resistance at the temperature of liquid nitrogen. Hot rolling created a fragmented substructure, and gradual annealing caused relaxation, polygonization, and, in some cases, local recrystallization.¹⁶ A second paper reports on changes occurring in tungsten single crystals as a result of rolling

or hydraulic extrusion, with subsequent annealing. For either mode of working, there were three characteristic degrees of deformation: precritical, critical, and hypercritical. Critical deformation is characterized by the formation of a cellular structure with sharp subboundaries, while preserving the overall single crystal state. On gradually annealing the critically deformed single crystal, recrystallization takes place, and a more perfect single crystal structure is created.¹⁷

Studies have been performed which are concerned with primary and secondary recrystallization of polycrystalline tungsten. In the first of these, the microscopic changes brought about by heating cold-rolled tungsten were discussed. An initial stage of "serration" of the boundaries of the elongated grains of the rolled material was recognized, preceding the start of recrystallization. Time/temperature/recrystallization curves were given,¹⁸ and the recrystallization process taking place during the gradient annealing of sintered tungsten was studied. Although not necessarily for all recrystallization conditions, there was frequently a close correlation between the orientations of the most rapidly growing secondary recrystallized grains and the primary recrystallization matrix. The extent of the correlation was very dependent on the original type of texture and the conditions of gradient annealing; eg, the direction of motion of the hot zone relative to the rolling direction. Also a factor was the existence of micropores.¹⁹ The mechanism responsible for secondary recrystallization of sintered and rolled tungsten was also studied. In the course of secondary recrystallization, large grains were formed as a result of the merging of similarly oriented crystallites. The boundaries between these particles vanished as a result of a redistribution of the dislocations constituting the boundary and their dissipation into adjoining grains.²⁰

Another factor reported as affecting the course of tungsten recrystallization is gas bubbles. Tungsten sheet deposited from tungsten hexafluoride was rolled at temperatures up to 1000° C and to thickness reductions of 95%. For one-hour annealing times, the minimum temperature for the onset of recrystallization was 1600° C; and, for complete recrystallization, 2100° C. Transmission electron microscopy showed many small [$\leq 0.05 \mu\text{m}$ ($< 500 \text{ \AA}$)] gas bubbles on dislocations and recovered subgrain boundaries. Annealing prior to rolling coarsened the gas bubbles and accelerated recovery and complete recrystallization at 1200° C.²¹

In summary, the literature suggests several factors which may be acting to promote the growth of large, recrystallized grains at the midthickness of wrought plate prior to its becoming generally recrystallized. There are apparently factors operative which greatly affect the temperature at which recrystallization takes place. For example, rolling tends to develop a $\{001\} \langle 110 \rangle$ texture in body-centered-cubic metals; and, when single crystals of this orientation were rolled and annealed, the temperature of recrystallization was very high. Since a rolled plate would be more highly textured at the surfaces than at the center, recrystallization at a given temperature might be expected to be initiated at the plate midthickness. In support of this possibility were the reported observations that recrystallization of rolled single crystals began first at either the edge or center, depending on the initial orientation. This behavior was presumably due to textural variations within the deformed crystal.

The large size of the observed midplate-thickness recrystallized grains may be a secondary recrystallization phenomenon. If the texture developed by rolling was particularly favorable, secondary recrystallization reportedly could occur due to a similarity in orientation between the secondary grains and the primary matrix. This similarity would permit rapid secondary grain growth by the merging of primary crystallites.

Heat Treatments for Optimizing the Workability of Tungsten

It is recognized that for maximum deformability, worked tungsten should not be recrystallized, but should be heat treated through the recovery stage and just to the point of recrystallization. Work has been performed in an attempt to characterize the effects of these heat treatments.

Structural changes taking place in rolled tungsten on prerecrystallization annealing were studied by X-ray diffraction and correlated with measurements of hardness and the elastic limit. Changes occurred at 400 - 500° C and at 900° C. The lower-temperature change is attributed to polygonization; the reason for the second change is uncertain, but may have been the pinning of dislocations by Cottrell atmospheres of impurity atoms.²² It is also reported that brittleness may be minimized by ensuring that the temperature in the final stages of reducing semifinished tungsten parts and also the annealing temperature employed to remove residual stresses never exceed 1100° C.²³ Fabrication studies have been made that consider the interrelated effects of degree of cold work, subsequent stress relieving heat treatments, the ductile/brittle transition temperature (DBTT), and tensile properties. Optimum forming characteristics occur in sheet stress relieved at 1100° C with 1 - 5% recrystallization. Increased amounts of cold working depress the DBTT in the rolling direction, but this action is true in the transverse direction only for a certain amount of cold work.²⁴ Another study reported the changes occurring in the mechanical characteristics of polycrystalline tungsten on prolonged annealing at 900° C. For tensile strength versus time, a sharp drop took place over the first two hours, followed by a steady, but less rapid, decrease over a considerably longer period. The elongation increased smoothly with time, tending to approach a constant value. This treatment was significant since it avoided recrystallization of the kind frequently accompanied by embrittlement.²⁵

A study has been made of the heat treatments that were performed in connection with the rolling of tungsten. An intermediate recrystallizing anneal resulted in some reduction in ductility, but annealing after final rolling had no effect on the ductility if carried out below the recrystallization temperature. Reducing the rolling temperature caused an increase in strength, but little change in the percent elongation. There was a minimum in the reduction in the area-rolling temperature curve at 800° C.²⁶

The substance of these various investigations indicates some factors to be considered in rolling and heat treating tungsten for maximum ductility. Intermediate recrystallizing anneals during rolling should be avoided to retain maximum ductility, and there are apparently certain rolling temperature ranges which are most conducive to promoting ductility in the rolled product. After rolling, nonrecrystallizing anneals at temperatures

below 1100° C lower the tensile strength and increase the elongation. At 900° C, times in excess of two hours produce maximum ductility. For optimum tungsten sheet formability, stress relieving to the point of producing a 1 to 5% recrystallized structure is suggested.

Fracture Characteristics, Brittleness, and the Ductile/Brittle Transition Temperature in Tungsten

Much work has been done in an attempt to develop an understanding of the factors which influence the fracture, brittle behavior, and DBTT of tungsten. Single-crystal studies have comprised much of the effort, while work with polycrystalline tungsten has utilized both sintered powder and cast material.

Tensile tests of single crystals of various orientations have shown a substantial tensile elongation from 20 to 480 K and show large systematic variations in tensile properties as a function of the crystallographic orientation. Even crystals of [100] orientation which are capable of sustaining less deformation than those of [110] and [111] orientations will plastically elongate on the order of 10% at 20 K. Necking always occurs before fracture if the crystal surface is perfect, indicating that tungsten is not inherently brittle but is extremely notch sensitive.²⁷ In a study of tungsten bicrystals with various crystallographic mismatches, the ductility was observed to vary according to the disorientation. For less than a six-degree mismatch, the ductility varied little from a single crystal. For larger angles, the bicrystal rapidly became brittle, with the greatest brittleness change occurring at six to eight degrees. The sharp change in properties was related to the strength of the intergranular boundary. The loss of strength may be partly due to the segregation of impurities at the intercrystalline interface and to the internal stresses arising from these impurities.²⁸

One phase of the brittleness problem which has received considerable attention is the DBTT and the factors which influence it. The DBTT is defined essentially as the highest temperature at which fracture occurs with no detectable plastic deformation. The effects of many variables have been studied among which are grain size, impurities, microstructural features, material origin, deformation, speed of deformation, and alloying. The relative effects of interstitial impurity content and grain size on the "cold shortness" of tungsten were studied. For oxygen and carbon levels not less than 0.005 to 0.010 wt %, the grain size produced during heat and mechanical treatment of vacuum-melted metal had a more pronounced effect than impurities.²⁹ In further work, the temperature of the transition from the absence to the presence of macroscopic plastic flow, T_T , and from failure by crack propagation to rupture by shear, T_F , were determined for fine and coarse-grain melted tungsten. On coarsening the grain size to about 700 μm , T_T was lowered from 684 to 365 K; T_F was 990 K. Below T_T , fracture takes place when a microcrack is nucleated; above T_T , the critical event in failure is crack propagation.³⁰

Another grain-size-related effect on the DBTT was the segregation of phosphorus to the grain boundaries as determined by Auger spectroscopy of intergranular fractures. The concentration of phosphorus was correlated with the DBTT, and the larger the grain size the more concentrated was the phosphorus and the more brittle the material.³¹ A Russian

reference reported on the combined effects of impurities and plastic deformation. Impurities in and adjacent to the grain boundaries of powder-metallurgy tungsten were resorbed during working, and the DBTT was lowered. This phenomenon was particularly marked in the case of hydrostatic extrusion.³²

Studies were made, using hardness measurements, of the DBTT of tungsten. Cracks near indentations close to the specimen edge were related to the DBTT. Tungsten was brittle below 330° C and ductile above 394° C.³³

It has been observed that the DBTT for tungsten varies, depending upon whether the material was of powder or melted origin. A study was conducted to find reasons for the 100° C higher DBTT of polycrystalline sintered tungsten, compared with melted material. A connection was established between low-stress failure, sintered tungsten, and grain-boundary voids or bubbles. In this way, the grain boundaries can be weakened, although no inclusions are present and may, therefore, control the fracture process. Gas bubbles or voids were present at the grain boundaries of sintered, but not melted, tungsten.³⁴ The brittle fracture of cold-worked sintered and electron-beam zone-refined tungsten was studied from 4.2 to 298 K. In sintered tungsten, a general microyield was observed only down to 202 K; for zone-refined tungsten, macroyielding occurred at all temperatures, with evidence for twinning below 202 K. The fracture stress for sintered tungsten was virtually independent of temperature, while the electron-beam-melted material showed a 2.3 times increase over the same temperature range. Fractography revealed rod-shaped and spherical voids in sintered, but not in melted, material. It is suggested that slip, induced by the local high-stress concentration in the region of a favorably oriented void, could cause the void to grow to a microcrack of critical size.³⁵

Fracture modes also differed between cast and sintered tungsten that was tested for creep behavior. Optical and replica electron microscopy were used to examine the fracture surfaces of creep specimens of both arc-cast and powder-metallurgy tungsten. The arc-cast material deformed ductilely and failed transgranularly, while the sintered tungsten was relatively brittle and failed intergranularly by the formation and linkup of creep cavities. Below 2000° C, these cavities were irregular in shape and tended to be flattened along the grain boundaries; at higher temperatures they became polyhedral. Since no evidence of grain-boundary precipitates was observed, the pores themselves are suspected of contributing to the brittleness.³⁶

Although not directly comparable with creep fractures, information on the fracture characteristics of vacuum-arc-remelted, 99.95% pure, industrial tungsten has been reported. This material was vacuum annealed for one hour at temperatures from 1000 - 2300° C and fractured by impact at room temperature. As the annealing temperature was raised, the portion of intergranular fracture increased. However, inclusions were observed to be present on the fracture surfaces and had various structures and complex chemical constitutions containing many elements (Mg, Al, Si, K, Ca, Cr, Fe, Ni, Mo, and W).³⁷

An attempt to determine the effect of rhenium additions on the DBTT of tungsten was difficult to evaluate. Rhenium increases the ductility of tungsten, mainly due to its grain-refining effect. Grain size has a marked, but unpredictable, effect on the DBTT. Rhenium lowered the DBTT of tungsten, but an increasing grain size also lowers the value. This effect suggests that, as in the case of pure iron, there is a grain size at which the DBTT is a maximum and that the DBTT value decreases with both increasing and decreasing grain sizes.³⁸ A second reference on the effect of rhenium additions reported that the temperature and strain-rate dependence of the yield stress decreased with increasing rhenium content. Also, the work-hardening rate at a one percent plastic strain for unalloyed tungsten increased rapidly with decreasing temperature, but was relatively insensitive in the rhenium alloys at 300 - 800 K. The reduced DBTT in the rhenium alloys arises from an increased plastic strain at crack tips due to increased dislocation mobility and multiplication rates.³⁹

The surveyed references have summarized several factors involved in understanding the problems of brittle fracture and DBTT in pure tungsten. Of primary interest is the finding that single crystals with scratch-free surfaces behave in a ductile manner, even at very low temperatures. The brittle behavior of scratched crystals, however, reveals the notch sensitivity of tungsten. The role of grain boundaries is indicated by the brittle behavior of bicrystals and of sintered polycrystalline material. In the latter case, particularly, impurities and voids at the grain boundaries are believed to be influential factors. Melted and annealed tungsten shows cleavage failure at normal temperatures, with a trend toward intergranular failure at high temperatures. The DBTT is generally higher for sintered than for melted tungsten, probably because of the presence of grain-boundary voids which are stress risers and lead to microcracks.

The DBTT has been shown to be more sensitive to grain size than to certain impurities; a coarser grain size tends to lower the DBTT. For embrittling impurities which segregate at the grain boundaries (phosphorus, for example), grain coarsening reduces the grain-boundary area and concentrates that impurity, thus reversing the grain-size effect.

Small rhenium additions lower the DBTT, but also reduce the grain size. Since increasing the grain size generally lowers the DBTT, a grain size at which the DBTT is a maximum is suggested. Another possible mechanism by which rhenium may lower the DBTT is by bringing about an increased plastic-strain capacity for blunting the tips of microcracks.

A possible mechanism explaining the lowered DBTT of worked tungsten is that in the course of working, grain-boundary impurities are resolutioned and, therefore, less apt to be embrittling.

Effect of Impurities and Small Alloy Additions on the Properties of Tungsten

Because of tungsten's brittleness and the difficulties of fabricating it, much attention has been paid to the effect of impurities on its properties. Most references attempted to relate impurities to mechanical properties. In single-crystal tungsten, increased carbon contents

(16 - 32 ppm) raised the microyield strength, presumably by increased carbide formation at the dislocation sites.⁴⁰ Single crystals of tungsten alloyed with 0.1 at % osmium and 0.1 and 4.3 at % rhenium were prepared by electron-beam melting. Plates cut along (100) were bend tested. The stress/strain proportionality limit increased as a result of alloying, while the degree of work hardening and its temperature dependence diminished. The cold-embrittlement threshold was reduced to the greatest extent by adding only traces (0.1 at %) of osmium or rhenium.⁴¹ In another study, effect of carbon additions on the tensile properties of tungsten and tungsten-0.35 wt % tantalum single crystals was determined. A marked effect on yield strength was observed on material quenched from 2200 or 2450° C. In both crystals, a yield stress maximum at 600° C, concurrent with a loss in ductility, was attributed to carbide precipitation.⁴²

When impurities in polycrystalline tungsten are investigated, the effects of their being concentrated at the grain boundaries must be considered. Grain-boundary impurities in sintered tungsten were identified by Auger spectroscopy, and their effect on properties was determined. Strength and ductility were highest in tungsten of highest purity. Potassium appeared to be least damaging and, possibly, of value; however, silicon, sulfur, calcium, barium, phosphorus, nitrogen, and oxygen were, to varying degrees, unfavorable.⁴³ In another study, grain boundaries were examined in both sintered and electron-beam-melted tungsten. Intercrystalline fractures in both materials contained the oxide (WO_2). When carbon had been added as a deoxidizer, the carbide (W_2C) was present.⁴⁴ Further work considered the effect of temperature on the yield strength of polycrystalline industrial tungsten of various purities. The temperature-dependent component of yield strength was practically independent of its impurity content, heat treatment, and the structural state of the metal at ordinary and liquid-nitrogen temperatures. The relation between grain size and yield strength also depended little on the content and distribution of impurities.⁴⁵ A study was made on the segregation of the impurities of vacuum-rolled tungsten with reference to cold shortness (presumed to be the DBTT). Microhardness measurements were made at the edge and center of various grains as a function of the annealing time. Vacuum annealing at 1500 K increased the hardness at the grain boundaries for the first one-half hour, after which a reverse effect prevailed.⁴⁶

Tensile tests were performed to evaluate the effect of oxygen, nitrogen, and carbon impurities on the deformability of polycrystalline tungsten. The tensile tests showed three types of deformation behavior associated with various temperature ranges: Range I - low-temperature brittleness; Range II - ductile behavior at an intermediate temperature; Range III - ductile behavior at a high temperature with incipient grain-boundary embrittlement. Contaminants affect the metal differently in each range. They are in solid solution and also present in compound form as grain-boundary precipitates. As dissolved interstitials, Range II is affected; grain-boundary precipitates exert the greatest influence in Ranges I and III.⁴⁷ In other work involving interstitial impurities, their effect on mechanical properties was examined, and a technique was developed to remove them from tungsten.⁴⁸ Also, in an electron microscopic investigation of intergranular failure in cast tungsten, the formation of polyhedral cavities at the grain boundaries was theorized as having been caused by condensing oxide vapor.⁴⁹

The high-temperature properties of cast tungsten containing up to 0.2% carbon have been studied. Properties were measured from 1200 to 2000° C. Carbon increased the tensile strength up to 1500° C, and the effect was greater with increasing carbon content and decreasing test temperature. Above 1500° C, carbon did not strengthen the metal; and, at 1800 - 2000° C, the tensile and creep strengths were lower than those of pure tungsten. Tungsten-carbon alloys had superplastic properties around 2000° C. Carbon also slightly raised the recrystallization temperature.⁵⁰ In addition to the recrystallization temperature, impurities may also affect grain growth. For tungsten containing traces of aluminum, the grain-growth rate was 300 times less at a recrystallization temperature of 1300° C than for tungsten not containing aluminum.⁵¹

Reportedly, interstitial impurities which might otherwise be detrimental to the properties of tungsten may be made less damaging by alloy additions. When rhenium is added to tungsten, the improvement in low-temperature ductility is thought to be caused by the removal of the interstitial elements from the matrix as a result of rhenium-induced clustering.⁵²

The contents of this section tie in closely with the preceding one, but it was intended that the emphasis here be on the effect of impurities and small alloy additions on other properties of pure tungsten.

Of the impurities occurring in tungsten, those classified as interstitials (oxygen, nitrogen, and carbon, particularly the latter) have received considerable study. All three may occur in solution and as grain-boundary precipitates as a consequence of both concentration and heat treatment. In solution, they affect the ductile behavior at intermediate temperatures; as precipitates they tend to promote brittle behavior at low and high temperatures. Increasing the carbon content tends to raise the microyield stress, but the strengthening effect diminishes and carbon may actually lower the strength at very high temperatures. A means of tying up interstitials and increasing ductility may be by the addition of small amounts of rhenium or osmium.

In investigating the effects of other impurities, all (except possibly potassium) caused decreases in the strength and ductility of very pure tungsten. Neither did these impurities affect the temperature-dependent component of yield stress or the grain size/yield stress relationship. Aluminum was found to highly restrict grain growth at 1300° C, compared with normal growth in pure tungsten.

Of the deliberately added impurities, one effect of rhenium was mentioned previously. In addition, small quantities of rhenium and osmium were observed to raise the proportional limit, and lower the degree of work hardening and reduce its temperature dependence.

Surface Treatments and/or Imposition of other Conditions Designed to Augment Ductility or Reduce Cracking Tendency of Tungsten during Working

Since tungsten has been shown to be inherently ductile, but is notch sensitive to a high degree, there has been some effort devoted to examining various surface treatments,

environmental conditions, and other treatments which might ease the notch problem. The effect of protective coatings on the plastic deformation of tungsten and on tungsten that has been subjected to in-service loading has been studied. Both titanium coatings and surface-active media (eg, alkali dichromates) had a major effect on the impact strength and the amplitude-dependent (ie, plastic-deformation-related) component of internal friction of polycrystalline tungsten. However, the possible reduction in surface energy of tungsten as a result of a titanium film did not constitute a decisive factor in improving the mechanical properties of tungsten.⁵³ In another experiment, one-micrometer titanium films on unannealed tungsten slightly lowered the DBTT from 190 to 160° C. After annealing, however, the DBTT was either raised or lowered, depending on the temperature. On annealing at 800° C, the DBTT increased from 190 to 230° C.⁵⁴

Deformation, with the simultaneous application of an electric current, has been investigated. Rolling of tungsten and tungsten-rhenium wires into strips a few micrometers thick was facilitated by an electric current applied directly in the center of deformation. This current augmented the ductility and prevented the development of cracks. The technique was especially useful for W-27 Re alloy which otherwise was almost unworkable. However, a careful preliminary choice of working parameters was required.⁵⁵ In a similar reference, the increase in ductility of metals on passing an electric current through them while subjecting them to mechanical deformation was studied for tungsten and tungsten-rhenium alloy flat strips. The current flowing through the center of deformation while flattening the strips was said to intensify the dislocation movement and cause pinned dislocations to be set in motion. These effects were manifested as an increase in ductility.⁵⁶ In a third, somewhat different, report on the use of an electric current which also involved the environment around the material, tungsten was electropolished while being subjected to a four-point bend test. An effect was observed, but the abstract failed to indicate whether it was beneficial.⁵⁷

There has been other Russian work reported which indicates that argon, used as a protective atmosphere for high-temperature heat treatment of powder-metallurgy tungsten, causes a deterioration of the high-temperature properties, compared with those obtained using a vacuum atmosphere. Argon diffuses deeply into tungsten on high-temperature annealing and coalesces at the grain boundaries to form pores.⁵⁸ It is also said to have a delaying effect on the softening of tungsten on high-temperature annealing. This behavior is attributed to Cottrell pinning of dislocations by the diffusing argon atoms.⁵⁹

Mechanical treatments have been investigated which reportedly increase the ability of tungsten to withstand various kinds of mechanical deformation. For example, a study was made of the effect of torsional ultrasonic vibrations on the drawing of tungsten in the form of very thin sheet material. Application of vibration after previously heating the sheet to 350° C enabled parts of excellent structural quality and mechanical characteristics to be obtained with a relatively high degree of deformation. Oxidation of the tungsten surface was also greatly reduced in the presence of ultrasound.⁶⁰ In another study, tungsten samples of

sintered origin were subjected to the simple application of hydraulic pressure, and the influence of this pressure on plastic yielding and fracture at room temperature was studied. The effects of pressure were small and, in tungsten of sufficiently low impurity level, negligible. Results of measurements on the stress/strain behavior of recrystallized tungsten as a function of pressure showed that fracture stress increases and, with sufficient pressure, a distinct yield drop occurs, followed by substantial plastic deformation and work hardening.⁶¹

To summarize, in view of the notch sensitivity and low-temperature brittleness of tungsten, a number of investigators have taken the approach that there may be surface treatments or other means by which these tendencies may be lessened. Titanium coatings and surface-active media have beneficially affected some properties of polycrystalline tungsten, but the titanium was not a decisive factor in improving the mechanical properties.

Application of an electric current to the center of deformation while rolling tungsten and tungsten-rhenium alloys was said to increase dislocation mobility, thereby raising ductility and lowering the incidence of cracking. The method was particularly successful with the very difficult-to-work alloy (tungsten-27 wt % rhenium).

Argon is normally thought of as an inert atmosphere, suitable for protecting tungsten while heating for working. However, vacuum may be more satisfactory since argon reportedly diffuses into tungsten and embrittles it by coalescence into grain-boundary pores.

Mechanical treatments have also been tried with some success. Application of torsional ultrasonic energy has enhanced the drawing to shape of thin tungsten sheet parts. High prepressurization treatments of tungsten were relatively ineffectual in enhancing the mechanical properties of the metal.

REFERENCES

1. Ludwig, H. J.; "Principles and Applications of Pressing Methods, III, [Flowturning]", *Bänder-Bleche-Rohre*, **10**, (11), pp 667 - 676; November 1969 (German).
2. KolomoGOROV, V. L., Chal'sky, V. I., and Kozlov G. D.; "Theory of the Hydro-Extrusion of Brittle Metals, (Molybdenum, Zinc, Beryllium, and Tungsten)", *Metallov i Metallovedenie*, **23**, (1), pp 170 - 173 (1967).
3. Bobrowsky, A.; "Ultra-High Pressure: A Powerful Metalworking Tool", *Mat Design Engineering*, **61**, (6), pp 96 - 99 (1965).
4. Haegland, B. F., Eftestol, B., and Schreiner, K.; "Explosive Hot Forming of Steels and Refractory Metals", *Proc NATO Advanced Study Inst, High Energy Rate of Working of Metals, Norway, September 1964*; (1), pp 160 - 168 (1966).
5. Babel, H. W. and Bonesteel, R. M.; "Cutting and Forming of Tungsten Sheet", *Metal Progress*, **87**, (4), pp 66 - 71 (1965).
6. Olbom, M. J.; "Solid State Welding of Reactive and Refractory Metals", *Mat Design Engineering*, **61**, (4), pp 106 - 109 (1965).
7. Ivashchenko, R. K., Mil'man, Yu. V., Trefilov, V. I. and Khomenko, G. E.; "Anisotropy of Structural Elements in Worked Refractory Metals", *Fizika Metallov i Metallovedenie*, **39**, (1), pp 81 - 87; January 1975 (Russian).
8. Izotov, V. M. and Levtonov, I. P.; "Porosity and Lamination of Refractory Metals", *Sbornik Trudov Vses N-I Proekt Inst Tugoplavk Met Tverd Splavov*, (14), pp 205 - 209 (1973) (Russian).
9. Vrublevskaya, Z. V. and Orlov, L. G.; "Layer Structure of Cold Rolled Molybdenum", *Fizika Metallor i Metallovedenie*, **22**, (2), pp 286 - 289 (1966) (Russian).
10. Gilbert, A.; "A Fractographic Study of Tungsten and Dilute Tungsten-Rhenium Alloys", *J Less-Common Metals*, **10**, (5), pp 328 - 343 (1966).
11. Müller, D., Schlaubitz, K., and Wadewitz, H.; "The Structure and Properties of Rolled and Annealed Molybdenum and Tungsten Single Crystal", *Ber Internat Symposium Reinststoffe in Wissenschaft u. Technik, Dresden (1965). Teil 3; Realstruktur u. Eigenschaften Von Reinststoffen*, pp 747 - 754; (1967) (German).
12. Fujü, T., Ohba, Y., and Tamura, Y.; "Deformation and Recrystallization of (001) [110] Single Crystals of Pure Tungsten Rolled at 200° C and Tantalum at 100° C", *Trans Japan. Inst Metals*, **16**, (4), pp 219 - 224 (April 1975).

13. Kobylanski, A., Levy, J., and Goux, C.; "Critical Strain Values for the Recrystallization of Oriented Single Crystals of Niobium, Molybdenum and Tungsten Deformed by Compression", *Compt Rend*, **273C**, (2) pp 128 - 130; July 12, 1971 (French).
14. Fujü, T., Ohba, Y., and Tamura, Y.; "Rolling Deformation and Recrystallization of (111) [112] Single Crystals of High Purity Tungsten, Molybdenum, and Tantalum", *J Less-Common Metals*, **39**, (1), pp 161 - 172; January 1975.
15. Rieck, G. D., Vaessen, G. H. G., and Vogel, D. L.; "Microhardness and Microhardness Anisotropy of Tungsten", *Trans Met Soc AIME*, **242**, (4), pp 575 - 578; April 1968.
16. Tiraspolsky, V. I., et al; "Microstructure and Properties of Worked and Annealed Tungsten Single Crystals", *Fizika Metallov i Metallovedenie*, **29**, (1), pp 175 - 179; January 1970 (Russian).
17. Novikov, I. I. and Tiraspolsky, V. I.; "Structural Changes in the Plastic Deformation and Annealing of Tungsten Single Crystals", *Fizika Metallov i Metallovedenie*, **35**, (5), pp 1040 - 1044 (1973) (Russian).
18. Pivk, E.; "The Primary Recrystallization of Molybdenum and Tungsten", *Planseeber Pulvermet*, **16**, (4), pp 227 - 282; December 1968, (German)
19. Kralina, A. A., Puzanova, L. V., and Sokolov, B. K.; "Relationship between the Secondary Recrystallization Crystallites and the Texture of Primary Recrystallization in the Gradient Annealing of Commercial Tungsten", *Fizika Metallov i Metallovedenie*, **41**, (1), pp 83 - 90; January 1976 (Russian).
20. Davydov, Yu. I., Krishtal, M. A., and Lerner, M. A.; "Mechanism of Secondary Recrystallization", *Fizika i Khim Obrabot Mat*, (1), pp 114 - 118; January - February 1970 (Russian).
21. Farrell, K., Schaffhauser, A. C., and Houston, J. T.; "Effect of Gass Bubbles on the Recrystallization of Tungsten", *Met Trans*, **1**, (10) pp 2899 - 2905; October 1970.
22. Spektor, E. N. and Gorelik, S. S.; "Structural Changes in Rolled Tungsten on Pre-Recrystallization Heating", *Tsvetnaya, Met* (1), pp 103 - 104 (1967) (Russian).
23. Gushov, V. L. and Panovko, V. M.; "Brittleness of Tungsten on Annealing", *Metallovedenie i Term Obrabot Metallov*, (5), pp 60 - 61 (1970) (Russian).
24. Hegedus, A. E. and Fusco, R. S.; "The Influence of Stress Relieving on Optimum Quality Tungsten Sheet", *Met Soc Conf AIME, Refractory Metals and Alloys, IV, Research and Development*, pp 705 - 725; French Lick, October 1965 (1969).
25. Z asimchuk, E. E. and Sviridovsky, Yu. M.; "Study of the Kinetics of the Isothermal Softening of Tungsten at 900° C", *Problemy Prochnosti*, (7), pp 61 - 62; July 1974 (Russian).

26. Osipov, V. G., Ushakov, E. V., Drobysheva, E. K., and Borisov, A. E.; "The Effect of Treatment Conditions on the Mechanical Properties of Tungsten", *Protsessy Formoizmeneniya Met i Splavov*, pp 144 - 151; Russian Collection, Published Nauka, Moscow (1971) (Russian).
27. Beardsmore, P. and Hull, D.; "Deformation and Fracture of Tungsten Single Crystals", *J Less-Common Metals*, **9**, (3), pp 168 - 180 (1965).
28. Yastryebkov, A. A. and Ivakin, Yu. P.; "Effect of the Angle of Intergranular Disorientation on the Brittleness of Tungsten Bicrystals", *Fizika Metallov i Metallovedenie*, **36**, (1) pp 135 - 139 (1973) (Russian).
29. Panovko, V. M. and Gurshov, V. L.; "The Effect of Interstitial Impurities and Grain Size on the Cold Shortness of Tungsten", *Protsessy Formoizmeneniya Met i Splavov*, pp 125 - 134; Russian Collection, published Nauka, Moscow (1971) (Russian).
30. Thornley J. C. and Wronski, A. S.; "The Grain Size Dependences of the Failure Mode and Ductility Transition Temperatures of Melted Chromium and Tungsten", *Metal Sci J*, **6**, pp 113 - 118; July 1972.
31. Joshi, A. and Stein, D. F.; "Intergranular Brittleness Studies in Tungsten Using Auger Spectroscopy", *Met Trans*, **1**, (9), pp 2543 - 2546; September 1970.
32. Shashkov, D. P.; "Effect of Plastic Deformation on the Brittleness of Tungsten", *Fizika Metallov i Metallovedenie*, **32**, (1), pp 131 - 138; July 1971 (Russian).
33. Oku, T., Sato, S., Yuhara, S., and Usui, T.; "Studies on Embrittlement [Ductile-Brittle Transition] of Molybdenum and Tungsten [In Relation to Temperature] by Hardness Measurements", *J Soc Mat Sci (Japan)*, **16**, (170), pp 876 - 882; November 1967, (Japanese, English Summary).
34. Wronski, A. and Fourdeux, A.; "The Ductile-Brittle Transition in Polycrystalline Tungsten", *J Less-Common Metals*, **8**, (3), pp 149 - 158 (1965)
35. Bilello, J. C.; "The Nucleation of Brittle Fracture in Sintered Tungsten at Low Temperatures", *Trans Met Soc AIME*, **242**, (4), pp 703 - 708; April 1968.
36. Rau W. R. and Williams, F. T., Jr; "Creep Failure Modes in Arc-Cast and Powder Metallurgy Tungsten", *IMS Proceedings, First Annual Technical Meeting*, pp 173 - 177 (1969).
37. Rasenin, G. V., Gavriluk, M. I., Zherdev, A. M., and Cherepanov, L. V.; "Electron Microscope and Microprobe Analyses of the Fracture of Tungsten", *Trudy Kirg Univ, Fiz*, (1), pp 11 - 13. (1972) (Russian).
38. Gilbert, A.; "A Fractographic Study of Tungsten and Dilute Tungsten-Rhenium Alloys", *J Less-Common Metals*, **10**, (5), pp 328 - 343 (1966).

39. Raffo, P. L.; "Yielding and Fracture in Tungsten and Tungsten Rhenium Alloys", *J Less-Common Metals*, **17**, (2), pp 133 - 149; February 1969.
40. Galyon, G. T. and Stark, P.; "Microstrain Characteristics of Single Crystalline Tungsten and Its Alloys", [*Met Soc Conf AIME*], *Refractory Metals and Alloys, IV, Research and Development*, pp 185 - 201; French Lick, October 1965 (1969).
41. Beloas, O. A., Minakov, V. N., Ovsienko, D. E., Sosnina, E. I., and Trefilov, V. I.; "Effect of Alloying on the Structure and Mechanical Properties of Tungsten Single Crystals", *Akad Nauk Ukr SSR Metallofiz*, (62), pp 60 - 65 (1975) (Russian).
42. Schnitzel, R. H.; "The Effects of a Carbon Addition on the Tensile Properties of Tungsten-0.35% Tantalum and Tungsten Single Crystals", *Trans. Quart Amer Soc Met*, **58**, (1) pp 74 - 84 (1965).
43. Benesovsky, F., et al; "The Determination of Grain Boundary Impurities in Sintered Tungsten and Their Effects on Its Properties", *Planseeber Pulvermetall*, **23**, (2), pp 101 - 120; June 1975 (German).
44. Krumpkhol'd, R.; "Grain Boundary Precipitation in Molybdenum and Tungsten and Its Effect on Some of Their Properties", *Novye Tugoplavk, Metal Materialy*, pp 55 - 76; Russian Collection published Mir, Moscow (1971) (Russian).
45. Gordienko, L. K., Kopetsky, Ch. V., and Panovko, V. M.; "Effect of Temperature on the Yield Stress of Polycrystalline Tungsten of Industrial Purity", *Tzvest Akad Nauk SSSR, Metally*, (2) pp 190 - 198; March - April 1970 (Russian).
46. Krupin, A. V., Shvets, O. V., Linetsky, B. L., and Chernyshev, V. N.; "Segregation of Impurities in Vacuum-Rolled Tungsten", *Tzvest VUZ Tsvetnaya Met*, (4), pp 137 - 140; July - August 1968 (Russian).
47. Pink, E. and Sedlatschek, K.; "Effect of Impurities on the Deformability of High Melting Point Metals", *2nd Europäisches Symposium über Pulvermetallurgie*, Stuttgart, Mai 1968 **1**, (3,6), 15 pages; May 1968.
48. Stein, D. F. and Low, J. R., Jr; *Influence of Interstitial Impurities on the Low-Temperature Strength and Ductility of BCC Metals (and the Removal of These Impurities from W, Mo, and Fe)*, [U.S.] Dept. of Commerce Clearinghouse Report, (AD631708), 28 pages (1966).
49. Blenkinsop, P. A., and Morton, P. H.; "The Influence of Oxygen Upon Intergranular Fracture in Cast Tungsten", *J Inst Metals*, **96**, (8), pp 248 - 251; August 1968.
50. Pod'yachev, V. N. and Gavril'yuk, M. I.; "Effect of Carbon on the Strength of Tungsten at High Temperatures", *Probl Prochn*, (12), pp 81 - 83; December 1975 (Russian).

51. Aleksandrov, L. N. and Kogan, A. N.; "On the Theory of the Influence of Impurities on the Growth Rate of Grains During Recrystallization of Metals", *Phys Metals Metallogr*, **23**, (4), pp 94 - 99 (1967) [Translation-Permagon].
52. Wukusick, C. S.; "The Rhenium Ductilizing Effect", *[Met Soc Conf AIME], Refractory Metals and Alloys, IV, Research and Development*, pp 231 - 245; French Lick, October 1965 (1969).
53. Amonenko, V. M., Azhazha, V. M., Shapoval, B. I., Bondarenko, N. P., and Kovtun, G. P.; "Effect of Coatings and Liquid Media on the Plastic Deformation of Tungsten", *Fizika Khim Obrabot Mat* (1), pp 120 - 122; January - February 1975 (Russian).
54. Azhazha, V. M., Amonenko, V. M., and Kovtun, G. P.; "Effect of Titanium Coatings on the Temperature of the Brittle Transformation in Tungsten", *Fizika Khim Obrabot Mat*, (2), pp 138 - 139; March - April 1969 (Russian).
55. Klimov, K. M., Shnyrev, G. D., Novikov, I. I., and Isaev, A. V.; "Electroplastic Rolling of Tungsten and Tungsten-Rhenium Wires into Strip of Micron Cross Section", *Tzv Akad Nauk SSSR Met*, (4), pp 143 - 144; July - August 1975 (Russian).
56. Klimov, K. M., Shnyrev, G. D., and Novikov, I. I.; "Electroplasticity of Metals", *Doklady Akad Nauk SSSR*, **219**, (2), pp 323, 324; November 11, 1974 (Russian)
57. Rovinsky, B. M., Baranov, Yu. V., Kostyukova, E. P.; "Effect of Polishing on the Substructure During Deformation of Tungsten Single Crystals", *Fizika Tverdogo Tela*, **16**, (11), pp 3207 - 3211; November 1974 (Russian).
58. Manayeva, Ye. N. and Mordyuk, V. S.; "Influence of an Inert Medium on the Failure Mechanism of Tungsten in Durability Tests", *Struktura i Svoystva Monokristallov Tugoplavkikh Metallov*, pp 192 - 197. Tzdv Nauka, Moscow (1973); [English Translation - Foreign Technology Div. W-P AFB, Ohio, Report FTD-HC-23-2465-74].
59. Mordyuk, V. S., Sinitsyn, G. F., and Cherkoshin, V. I.; "Effect of an Argon Medium on the Softening of Tungsten at Temperatures Corresponding to Polygonization and Recrystallization", *Fizika i Khim Obrabot Mat*, (6) pp 140 - 142; November - December 1969 (Russian).
60. Severdenko, V. P., Pashchenko, V. S., and Skachko, Yu. V.; "Study of the Drawing of Tungsten Subject to Torsional Ultrasonic Vibrations", *Fiz Khim Obrab Mater*, (3), pp 152 - 154; May - June 1976 (Russian).
61. Das, G. and Radcliffe, S. V.; "Effects of Hydrostatic Pressure on the Mechanical Behavior of Tungsten", *[Japan Inst Metals] Internat Conf on Strength of Metals and Alloys*, pp 218 - 221; Tokyo, September 1967 (1968).

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