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DEFORMATION OF POLYCRYSTALLINE MgO AT ELEVATED TEMPERATURES

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ABSTRACT

Stress-strain curves for five types of polycrystalline MgO are presented as a function of temperature. All types were nominally dense and pure but differed in grain size, composition, and porosity. Above 1200° C deformation occurred by grain boundary shearing accompanied in some cases by slip; below 800° C, specimens fractured primarily by grain boundary parting with little permanent strain. Between 800° C and 1200° C, one type deformed plastically by slip; the other four types were brittle. The observed behavior is analyzed in terms of the presence of mobile dislocations, the resistance to dislocation motion, and the strength of grain boundaries.

At the time this work was done the writers were, respectively, research assistant and professor of ceramic engineering, Department of Mineral Technology of the College of Engineering, and Inorganic Materials Research Division of the Lawrence Radiation Laboratory, University of California at Berkeley. S. M. Copley is now associated with the Advanced Materials Research and Development Laboratory, Pratt & Whitney Aircraft, North Haven, Connecticut.

I. INTRODUCTION

In crystals with the NaCl structure, slip can occur on two families of slip systems. In those with ionic bonding, at low temperatures, dislocations move on $\{110\}\ \langle 1\bar{1}0\rangle$ slip systems producing straight slip steps; at somewhat higher temperatures they can also move on $\{001\}\ \langle 1\bar{1}0\rangle$ slip systems producing slip steps that are wavy.[1-3] For a polycrystalline material to maintain continuity during plastic deformation, its grains must be able to undergo general changes in shape. Many years ago, von Mises pointed out that a general change in shape requires shearing on five independent slip systems.[4] Groves and Kelly have shown that in NaCl-type crystals slip must occur on both the $\{110\}\ \langle 1\bar{1}0\rangle$ and the $\{001\}\ \langle 1\bar{1}0\rangle$ families to provide five independent slip systems; the $\{110\}\ \langle 1\bar{1}0\rangle$ family alone provides only two.[5] Accordingly, polycrystalline AgCl, NaCl, and KCl are found to be brittle at low temperatures but become ductile at the temperatures where slip on both $\{110\}\ \langle 1\bar{1}0\rangle$ and $\{001\}\ \langle 1\bar{1}0\rangle$ families is possible.[2,6,7]

Hulse, Copley, and Pask have measured the yield stress for $\{110\}\ \langle 1\bar{1}0\rangle$ and $\{001\}\ \langle 1\bar{1}0\rangle$ slip in MgO up to 1600° C.[8] Their measurements suggest that slip on both families of slip systems and hence ductility should be possible in polycrystalline MgO, above 600° C; however, polycrystalline MgO with ductility comparable to polycrystalline AgCl, NaCl, or KCl has not been reported.[8,9] Only at temperatures in the neighborhood of 1200° C has polycrystalline MgO been observed to strain significantly prior to fracture, and, in this case, the straining was attributed to grain boundary shearing.[9]

This investigation was concerned with an exploratory study of the effect of structure* on the mechanical behavior of nominally dense polycrystalline MgO. Specimens from five sources produced by different fabrication methods were used.

II. EXPERIMENTAL PROCEDURE

A. Types of Polycrystalline MgO

The composition of each type of polycrystalline MgO was determined by spectrographic analysis. The constituents are reported in Table I as oxides of the elements. A description of each type follows.

Type 1 was made in the authors' laboratory using a technique based on one described by Rice.[10] In brief, a mixture of powdered MgO with 3% LiF was hot-pressed at 1000° C at a pressure of 3000 psi for about 30 min in a graphite die in a vacuum (10^{-3} mm Hg). The resulting compact was then fired at 1300° C for 4 hrs in air. This procedure resulted in a transparent polycrystalline MgO containing approximately 75 ppm of Li† with a density of 3.579§ and with the microstructure shown in Fig. 1. The grain size was uniform, the largest cross sections being about 15μ. These specimens were called Type 1 (S.G.). Some of this type was given

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* Structure is used in the broad sense to include composition, microstructure, flaws, etc. Microstructure refers to the geometric distribution of identifiable grains and phases.

† Private communication from Roy W. Rice states that radio-tracer techniques indicate that such specimens contain approximately 0.08% F.

§ All reported density values were obtained by use of Archimedes principle and are thus comparable; x-ray density value for MgO single crystal is 3.5733.

a high temperature anneal to cause grain growth. After this anneal the grains varied in size from region to region, and grain cross sections up to 100μ were observed. These specimens were called Type 1 (L.G.).

Type 2 was obtained from the Honeywell Research Center, Hopkins, Minnesota, and was formed by an isostatic pressing and sintering method. It was white and translucent with a density of 3.546 and with the microstructure shown in Fig. 2. A number of very small pores can be seen within the grains and on the grain boundaries. The largest grain cross sections are about 50μ.

Type 3 was obtained from the Avco Corporation, Wilmington, Massachusetts. It was made by hot pressing in an alumina die at about 10,000 psi pressure and a temperature of about 1100°C as described by Spriggs, Brissette, Rossetti, and Vasilos.[11] It was blue-grey in color and translucent with a density of 3.578 and with the microstructure shown in Fig. 3. A few pores can be seen at three grain junctions. The largest grain cross sections are about 5μ.

Type 4 was obtained from the Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico. It was made by aqueous slip casting and then firing at 1600°C for about 2 hrs as described by Stoddard.[12] Its density was 3.452, and its microstructure is shown in Fig. 4. It is typical of crystalline materials sintered in the presence of a liquid phase in that the grains are rounded. Large pores are visible within the grains but not on the grain boundaries. The largest grain cross sections are about 150μ.

Type 5 was obtained from the Union Carbide Co. and was made by casting from the melt. It was locally fairly dense but contained some

large voids. A representative microstructure is shown in Fig. 5. A second phase and also cracks can be seen in the regions between grains. The distribution of the second phase is not continuous as it is in the Type 4 specimen. The largest grain cross sections are about 400μ.

B. Preparation and Examination of Specimens

Compression specimens of each type of polycrystalline MgO were cut with a diamond saw. The specimens were prisms with approximately square cross sections about 0.2 by 0.2 by 1.0 in. Coarse abrasive paper (220A) was used to grind specimen ends parallel.

Several specimens were carefully polished on one face to allow metallographic examination before and after deformation. The faces were (a) flattened by grinding with 600-grit SiC, (b) lapped with 1-2μ diamond grip, and (c) lapped with a high speed wheel using Linde A on Politex Polishing Disks (Style PA-K).* All specimens were chemically polished for 1 min in 85% ortho-phosphoric acid heated to about 150°C prior to deformation. This treatment produced, in general, a very smooth surface although pits were observed on a few grains. The etching solution used consisted of two parts 85% ortho-phosphoric acid and one part sulfuric acid. MgO single-crystal specimens immersed in this etch for 1 min at 26°C showed pits only on the {100} and {110} faces.

All photographs were taken with a Leitz Metallographic Microscope (MM5) using 4 by 5 in. Polaroid 55P/N film.

C. Stress-Strain Experiments

Stress-strain curves were obtained for each type of MgO at a number of constant temperatures. Specimens were loaded in compression at a constant force rate such that the initial stress rate was 20 psi/sec.

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* Geoscience Instrument Corp.

The stresses were calculated from initial specimen cross sections and are reported as normal rather than resolved shear stresses. Strains were determined by measuring the displacement of two small divot holes initially 0.5 in. apart on a side face of the specimen. All reported strains are true strains, the true strain being equal to the natural logarithm of one plus the engineering strain.

Specimens were heated in air in a furnace with $MoSi_2$ heating elements. Alumina buttons were placed between specimen ends and the loading rams, which were also made of alumina. Thin platinum sheets were placed between the specimen ends and the buttons as reaction barriers. A detailed description of the overall apparatus used in this investigation will be published separately.[13]

III. RESULTS

In a force rate experiment, the slope of the stress-strain curve is related to the strain rate at small strains by the equation

$$\frac{d\sigma}{d\epsilon} = \frac{d\sigma}{dt}\left(\frac{d\epsilon}{dt}\right)^{-1}, \qquad (1)$$

where σ is the applied force divided by the cross section of the undeformed specimen, ϵ is the strain, and t is time. It can be seen that for a constant force rate a small slope of the curve indicates a high strain rate; and a high slope, a low strain rate.

Figure 6 shows typical stress-strain curves for Type 1 (S.G.) specimens at temperatures ranging from 1000 to 1500°C. At 1000°C fracture occurred with little bulk strain, and the basic shape of the curve is different from those obtained at higher temperatures. At 1400 and

1500°C, after initial yielding, the stress-strain curves rapidly became flat indicating high strain rates; and the experiments were terminated by fracture of the alumina supporting buttons. At 1200 and 1300°C stress-strain curves are intermediate and terminated by fracture of the specimen.

After deformation it was noticed that the Type 1 (S.G.) specimens had lost their transparency, the 1400 and 1500°C specimens being appreciably opaque. These observations suggested that deformation might be occurring by grain boundary shearing and separation. To check this hypothesis, lines approximately 1μ wide were scribed with a diamond point on the mechanically and chemically polished surface of a Type 1 (S.G.) specimen. Figure 7 shows the surface of this specimen after it was strained 3% at 1400°C. The displacement of the scribed lines between grains A and B is clear evidence of grain boundary shearing. Of particular interest is the cleavage fracture developing in grain A. Such fracture is a necessary consequence of grain boundary shearing and allows for accommodation at three grain junctions. Although occasionally occurring within grains (as in grain A), such localized fracture most frequently occurred along the grain boundaries.

A second feature of interest in Fig. 7 is the ghost lines which were not present before the deformation experiment. These lines are the result of thermal etching and correspond to positions where the grain boundaries were stationary for a period of time at 1400°C. The final grain boundary positions are darker than the ghost lines. They are sharp bottomed due to the presence of the boundary, while the ghost lines are rounded due to additional thermal polishing after the boundary moved.

The translucency of the deformed Type 1 (S.G.) specimens is thus accounted for by localized fractures and grain boundary separations. These discontinuities also account for the high strain rates shortly after yielding because they reduce the cross-sectional area resisting deformation. This effect is emphasized with increasing strain because as the amount of localized fracture increases, the gaps between grains join together to form long intergranular cracks roughly parallel to the loading axis.

Figure 8 shows an intergranular crack in a Type 1 (L.G.) specimen deformed to fracture at 1300° C. Although little bulk straining by slip actually occurred, dislocation etch pits can be seen on the favorably oriented grains. In a large grain specimen, the gaps resulting from grain boundary shearing are quite large and can spread easily causing bulk fracture. Thus from 1000 to 1500° C, the Type 1 (L.G.) specimens were observed to fracture with little plastic strain.

Figure 9 shows typical stress-strain curves for Type 2 specimens at temperatures ranging from 400 to 1400° C. Experiments were stopped prior to fracture to obtain the complete specimens for metallographic examination. It can be seen that the Type 2 specimens were ductile well below 1200° C. Between 800 and 1200° C, parabolic-shaped stress-strain curves were obtained. At 1400° C, however, the curve was similar to that for the Type 1 (S.G.) specimen in that it rapidly became flat after initial yielding, suggesting that grain boundary shearing was occurring at this temperature. At 400° C the stress-strain curve was not parabolic and little bulk strain occurred, while at 600° C it was intermediate in nature. Figure 10 shows the surface of a specimen

deformed at 400° C. Many grain boundaries were cracked; however, little intragranular cracking was observed.

Figure 11 shows the surface of a Type 2 specimen deformed about 5% at 1000° C. This surface had been mechanically and chemically polished prior to deformation but was not treated after deformation. The dark spots were caused by the chemical polish and were visible on the surface before deformation. The wavy lines appeared after deformation and are "wavy slip" steps similar to those observed in NaCl, AgCl, and KCl. These steps were quite pronounced and appeared in almost all of the grains. They occasionally crossed grain boundaries and often became forked as they approached grain boundaries. Similar steps were observed on specimens deformed at 800° C but not at 600° C. The 1200 and 1400° C specimens were not prepared for this observation.

For purposes of comparison, stress-strain curves for the different types of polycrystalline MgO at 1000 and 1400° C are shown in Figs. 12 and 13, respectively. At 1000° C the stress-strain curves are similar in shape for all types except Type 2, which is the only one that showed deformation by slip. Also, metallographic examination of the surfaces of Types 1, 3, 4, and 5 specimens revealed no slip steps or other evidence that bulk slip had occurred. At 1400° C, grain boundary shearing or separation was quite evident in all of the types, and there were greater variations in the shapes of the stress-strain curves and yield stresses.

The Type 3 stress-strain curve at 1000° C was similar in shape to that for the Type 1 specimens except that it had a considerably higher strength at fracture; at 1400° C, the curve was similar to those for

Types 1 (S.G.) and 2 but it had a lower yield stress. The 1400° C specimen was observed to have markings on its side faces lying at 45° to the stress axis. These were interpreted as flow markings resulting from extensive shearing along boundaries oriented for maximum shear stress.

The Type 4 specimen exhibited the greatest strength at 1000° C, but it fractured at a low stress and strain at 1400° C. The Type 5 specimens had comparable stress-strain curves but were weaker. Figure 14 shows a surface after deformation at 1400° C. The darkening of the grain boundary regions suggests that this specimen deformed by a progressive shearing and fracture of the second phase.

IV. DISCUSSION

The interpretation of the differences in behavior of the various types of polycrystalline specimens is complicated by the fact that the number of specimens was insufficient to provide a systematic variation of parameters such as porosity, grain size and composition because of the unavailability of specimens with completely controlled structures. The types, however, can be roughly classified into two groups on the basis of the presence of a second condensed phase, as observed in the microstructures of Types 4 and 5 and suggested by the analyses shown in Table I. Types 1 and 2 were similar in that they were relatively pure and lacked a detectable second condensed phase. The analyses indicate that Type 3 was intermediate in that it may have had a small amount of second phase which was not optically distinguishable.

Type 2 specimens were the only ones that exhibited behavior comparable to that previously reported for AgCl, NaCl, and KCl. At 600° C

and below these specimens were brittle and their deformation was accompanied by a pulling apart of grain boundaries. At 800°C and above they were ductile and wavy slip steps were observed. A transition from brittle to ductile behavior thus occurred between 0.28 T_m and 0.35 T_m. In AgCl, NaCl, and KCl similar transitions were observed in tension at about 0.24 T_m, 0.44 T_m, and 0.40 T_m, respectively.[2,6,7]

Before comparing the behavior of the different types of polycrystalline MgO, the behavior of the Type 2 specimens will be considered in more detail. The deformation of these specimens can be further understood by comparing their stress-strain behavior to that of uniaxially stressed single crystals. Figure 15 gives yield stress values for MgO single crystals with <100> and <111> stress axes as a function of temperature.[8,14] A <100> stress axis results in equal, nonzero resolved shear stresses on four $\{110\}$ $\langle 1\bar{1}0\rangle$ slip systems. A <111> stress axis results in equal, nonzero resolved shear stresses on three $\{001\}$ $\langle 1\bar{1}0\rangle$ slip systems. In both orientations the resolved shear stresses on all other $\{110\}$ $\langle 1\bar{1}0\rangle$ and $\{001\}$ $\langle 1\bar{1}0\rangle$ slip systems are zero. The ratio of yield stresses for single crystals with a <111> stress axis to those with a <100> stress axis provides a measure of the relative mobility of dislocations on the two families of slip systems. This ratio is 13:1 at 350°C, 4.5:1 at 600°C, and 2.9:1 at 1600°C. Because slip on both families of slip systems is necessary to satisfy the von Mises requirement, an increase in ductility with increasing temperature would be predicted.

Also shown in Fig. 15 are yield stress values for the Types 1 (S.G.) and 2 polycrystalline specimens. It can be seen that the Type 2 specimens yielded at stresses considerably below those necessary to yield a

single crystal with a <111> stress axis. This fact is particularly significant because a <111> stress axis produces a near maximum resolved shear stress of 0.472 x the uniaxial stress on the three {001} <1$\bar{1}$0> slip systems. Thus, slip on these slip systems in the randomly oriented grains of the Type 2 polycrystalline specimens could not have resulted from the uniaxial stress alone but is evidence of additional stresses between grains.

These observations suggest the following explanation for the yielding behavior of the Type 2 specimens. With the application of stress, slip occurs first on the {110} <1$\bar{1}$0> slip systems because of their lower resistance to dislocation motion. Slip on these slip systems can provide, however, only two independent slip systems so that long range stresses build up in each grain. Above the brittle-ductile transition temperature these stresses force slip on the {001} <1$\bar{1}$0> slip systems and yielding occurs in the polycrystalline piece. (This phenomenon was quantitatively demonstrated for large grain polycrystalline LiF by Scott and Pask wherein a localized shear stress of 9000 psi was shown to develop on a slip system on which the resolved shear stress due to the applied load was only 880 psi.[15]) Below the brittle-ductile transition temperature these stresses cause grain boundary separation before they become sufficient to cause slip on the {001} <1$\bar{1}$0> slip systems and thus the specimen fractures without yielding. It follows that the brittle-ductile transition temperature in polycrystalline MgO should depend not only on the mobilities of dislocations on the {110} <1$\bar{1}$0> and the {001} <1$\bar{1}$0> slip systems but also on the strength of the grain boundaries.

It is also interesting to compare the strain hardening behavior of the Type 2 polycrystalline specimens to that of uniaxially stressed single crystals in the temperature range where polycrystalline deformation occurred predominantly by slip (800-1200° C). According to earlier measurements by Copley and Pask, single crystals compressed with <100> stress axes exhibit much less strain hardening than the Type 2 specimens.[14] Although four slip systems are equally stressed in this orientation, slip in a particular volume element of the crystal will generally occur on only two slip systems with orthogonal Burgers vectors. The interpenetration of slip on slip systems with Burgers vectors enclosing an angle of 60° (or 120°) is observed only where a transition occurs from one set of orthogonal slip systems to the other. Long range stress interactions exist between dislocations on these slip systems, and dislocations with Burgers vectors at 120° can react to form sessile dislocation networks which are observed where such transitions occur.[14,16,17] These observations suggest that greater strain hardening should result from interpenetrating slip on the oblique slip systems than on the orthogonal ones.

In polycrystalline MgO, slip on five independent slip systems in each grain is necessary for ductility and thus an interpenetration of slip on the oblique slip systems must occur. A measure of the amount of strain hardening that might be expected under these conditions is provided by the stress-strain behavior of single crystals with <111> stress axes. In this orientation, slip occurs on three $\{001\}\langle 1\bar{1}0\rangle$ slip systems providing that the ends are constrained from lateral movement. The Burgers vector of each of these slip systems is at 120° relative to the other two. A comparison of the previously reported

strain hardening behavior of <111> oriented single crystals to that of the Type 2 specimens shows that they are indeed comparable.[8,14]

After considering in some detail the Type 2 polycrystalline specimens, their behavior will be compared to that of the other types of polycrystalline MgO. Of particular interest are the behavior differences exhibited by the Types 1 (S.G.) and 2 specimens because of their similarities in structure. As discussed earlier, both of these specimen types were relatively pure and lacked a detectable second phase. They differed, however, in grain size, in the presence of Li and F in the Type 1 specimens, and in the presence of a dispersion of fine pores in the Type 2 specimens. The Type 1 specimens fractured without significant deformation at 1000°C and below, while the Type 2 specimens exhibited ductile behavior down to 800°C. Yielding was observed in the Type 1 (S.G.) specimens only at 1200°C and above where they deformed primarily by grain boundary shearing. As shown in Fig. 15, the Type 1 (S.G.) specimens generally supported greater stresses than those required to yield the Type 2 specimens without yielding themselves.

The less-ductile behavior of the Type 1 specimens may be caused by (a) lower dislocation mobility, (b) greater difficulties in initiating slip, or (c) grain boundary weakness. A reduction of the mobility of dislocations may be caused by the presence of Li and F. Gorum, Luhman, and Pask have shown that small solute additions can increase the yield stress of MgO single crystals by as much as four times.[18] Microhardness measurements on both types of specimens, however, detected no difference in hardness.

If dislocations and slip are initiated at only a few points in a grain, they will cause nonhomogeneous stress concentrations and fracture. Stokes and Li on the basis of room temperature tensile experiments on polycrystalline MgO concluded that mobile dislocations can be introduced through stress concentrations associated with pores.[19] Thus, it is possible that the presence of the small amount of pores in the Type 2 specimens may play a significant role in initiating slip and developing ductility. This explanation, however, would be ruled out at higher temperatures when the grain boundaries may also act as effective sources of mobile dislocations. Copley has shown that dislocations in subgrain boundaries in MgO single crystals become mobile at about 1000° C.[20]

Lastly, the presence of Li and F in the Type 1 specimens, preferably at grain boundaries, can be expected to have a significant effect on the structure, strength, and behavior of the grain boundaries. Modifications in their structure can increase the difficulties in forcing slip on $\{001\}$ $\langle 1\bar{1}0 \rangle$ slip systems in adjoining grains. On this basis, the Type 2 specimens have grain boundaries whose strength and characteristics are considerably more favorable for allowing the forcing of slip on $\{001\}$ $\langle 1\bar{1}0 \rangle$ slip systems and the development of wavy slip. The greater ductility of the Type 2 specimens than Type 1 (S.G.) does not appear to be attributable to some unknown favorable role of their larger grain size since the Type 1 (L.G.) specimen, whose grain size is still larger, showed no ductility at 1000° C.

The greater strength and lack of ductility of the Type 3 specimen at 1000° C can be attributed either to the smaller grain size or the presence of impurities. These factors, particularly the latter, could also be responsible for the lesser strength at 1400° C.

The Type 4 specimen showed the highest strength and a limited strain with no general yielding at fracture at 1000° C. The presence of a second phase at grain boundaries apparently prevented a sufficient build-up of localized stress either to initiate slip or to force flow on $\{001\}$ $\langle 1\bar{1}0 \rangle$ slip systems. The second phase may have also played a role in sealing cracks that may have developed. The weakness and lack of ductility at 1400° C indicated that the boundary phase was behaving as a liquid of relatively low viscosity.

The weakness of the Type 5 specimens at 1000° C can be attributed to the presence of large pores and cracks on their grain boundaries which cause early failure. At 1400° C, failure is apparently due to shearing along grain boundaries.

V. CONCLUSIONS

This exploratory study has provided several general conclusions as to the nature of the mechanical behavior of polycrystalline MgO.

1. The ductility of polycrystalline MgO is limited at high temperatures by grain boundary shearing and at low temperatures by the high stresses required for slip on the $\{001\}$ $\langle 1\bar{1}0 \rangle$ slip systems.
2. In an intermediate temperature range ductility is possible in compression provided that (a) slip can be initiated homogeneously, (b) the resistance to dislocation motion is not too great, and (c) the grain boundaries are sufficiently strong to resist separation or shearing.
3. With ductile deformation, the strain hardening of polycrystalline MgO is comparable to that of $\langle 111 \rangle$ oriented single crystals.

4. At low temperatures, the strength of polycrystalline MgO is seriously limited by the presence of grain boundary porosity.
5. At low temperatures, a continuous grain boundary phase is not necessarily detrimental to strength; at high temperatures, such a phase is generally weak and leads to fracture of the polycrystalline piece with little strain.

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Table I. Spectroscopic Analysis of Various Types of Polycrystalline MgO*

Constituents	Types of Polycrystalline MgO				
	1	2	3	4	5
Mg	Principal constituent of all 5 types				
Fe	--	--	0.025 %	0.03 %	0.1 %
Ba	--	--	--	0.004	--
Si	0.01 %	0.015 %	0.03	0.4	1.0
Mn	--	--	0.003	0.003	0.006
Al	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Ca	0.003	0.02	0.25	0.2	0.25
Cu	0.0008	0.0008	0.0008	--	0.0005
Ti	0.006	--	0.003	--	--
Li	0.0075	--	--	--	--
Ni	--	--	0.002	0.005	0.003
Cr	0.004	--	0.006	0.001	< 0.001
B	--	--	--	--	0.15
	0.0288	0.0408	0.3248	0.648	1.5155

* Analyses made by the American Spectroscopic Laboratories, San Francisco, California. Constituents reported as oxides of the elements indicated.

FIGURE LEGENDS

Fig. 1. Surface of an undeformed Type 1 specimen, polished and etched.

Fig. 2. Surface of an undeformed Type 2 specimen, polished and etched.

Fig. 3. Surface of an undeformed Type 3 specimen, polished and etched.

Fig. 4. Surface of an undeformed Type 4 specimen, polished and etched.

Fig. 5. Surface of an undeformed Type 5 specimen, polished and etched.

Fig. 6. Stress-strain curves for Type 1 (S.G.) MgO specimens loaded at 20 psi/sec.

Fig. 7. Grain boundary shearing in Type 1 (S.G.) MgO strained 3% at 1400° C.

Fig. 8. Intergranular fracture in Type 1 (L.G.) MgO deformed at 1300° C.

Fig. 9. Stress-strain curves for Type 2 MgO specimens loaded at 20 psi/sec.

Fig. 10. Intergranular fracture in Type 2 MgO deformed at 400° C.

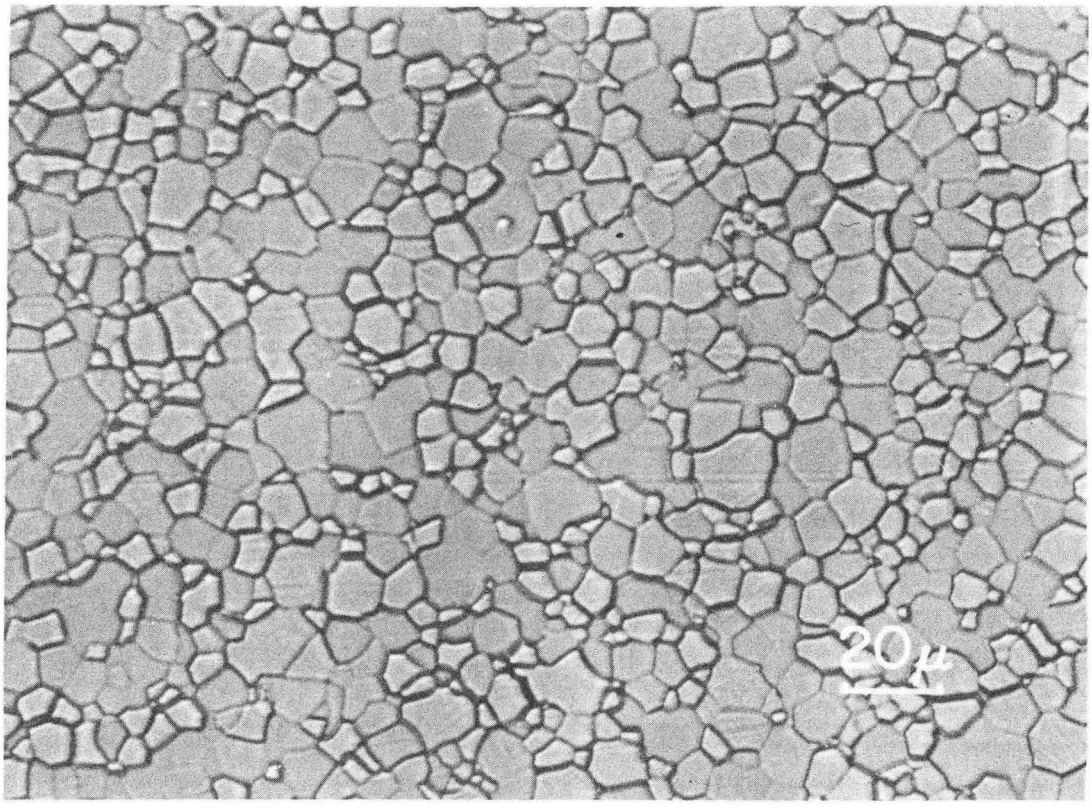
Fig. 11. "Wavy slip" in Type 2 MgO strained several percent at 1000° C.

Fig. 12. Stress-strain curves at 1000° C for various types of polycrystalline MgO. Loading rate 20 psi/sec.

Fig. 13. Stress-strain curves at 1400° C for various types of polycrystalline MgO. Loading rate 20 psi/sec.

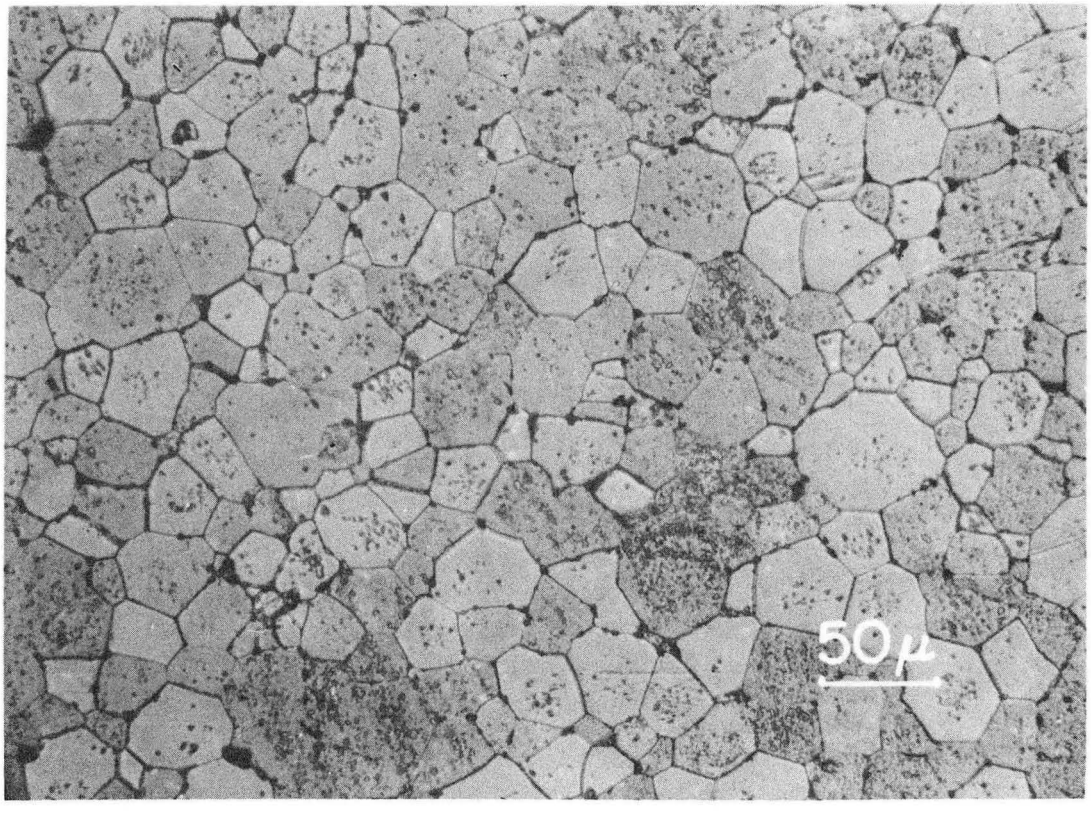
Fig. 14. Type 5 MgO deformed at 1400° C showing fracture of boundary phase.

Fig. 15. Yield stress vs temperature for the $\{110\}\langle 1\bar{1}0\rangle$ and $\{001\}\langle 1\bar{1}0\rangle$ slip systems, and for the Type 1 and Type 2 specimens.



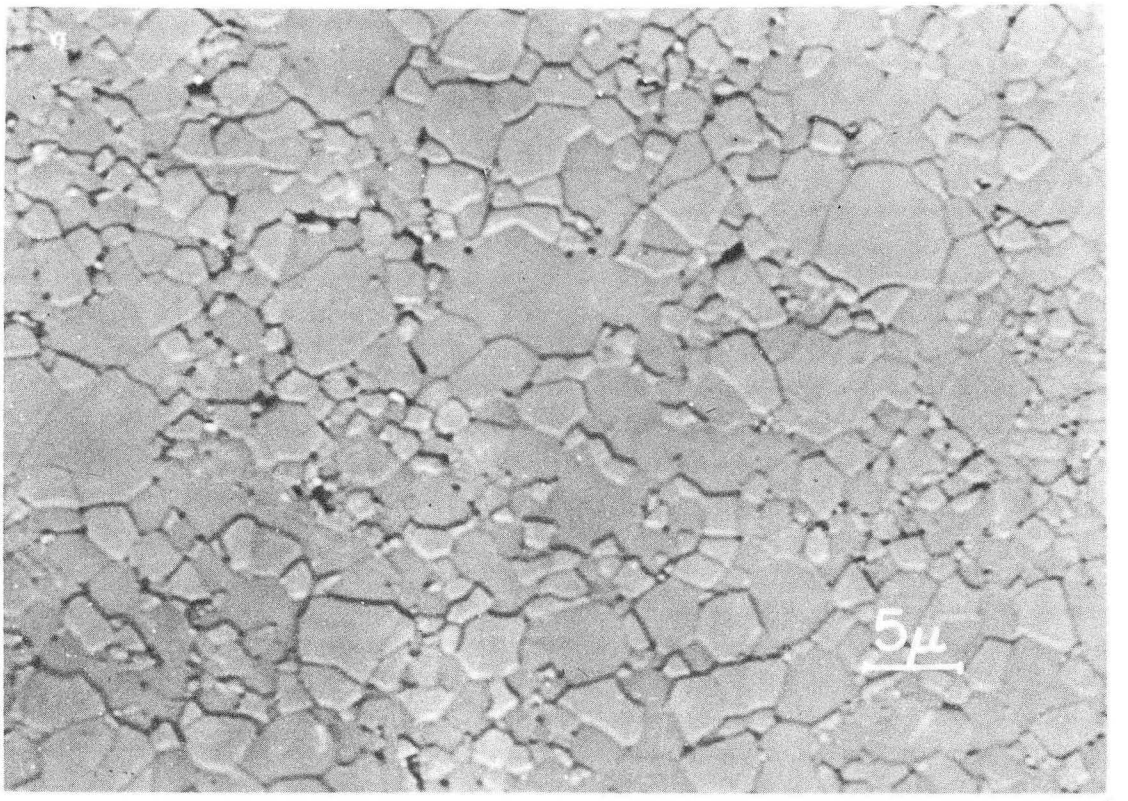
ZN-4706

Fig. 1



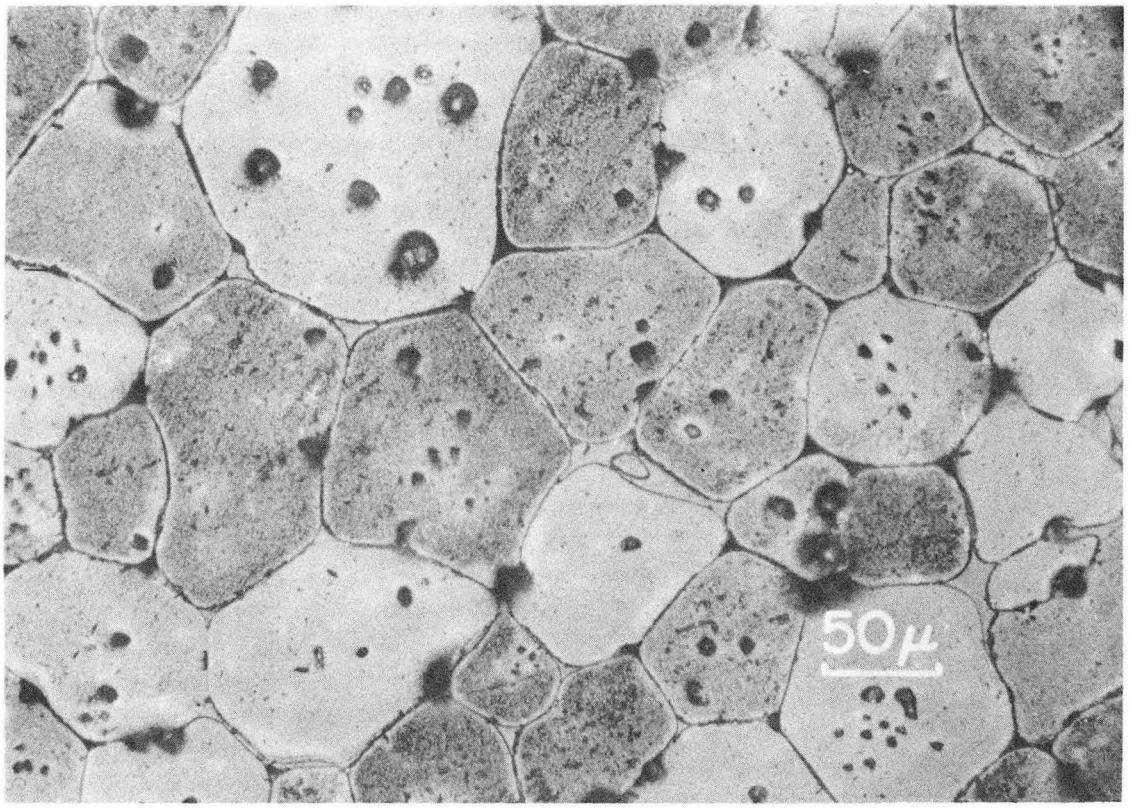
ZN-4711

Fig. 2



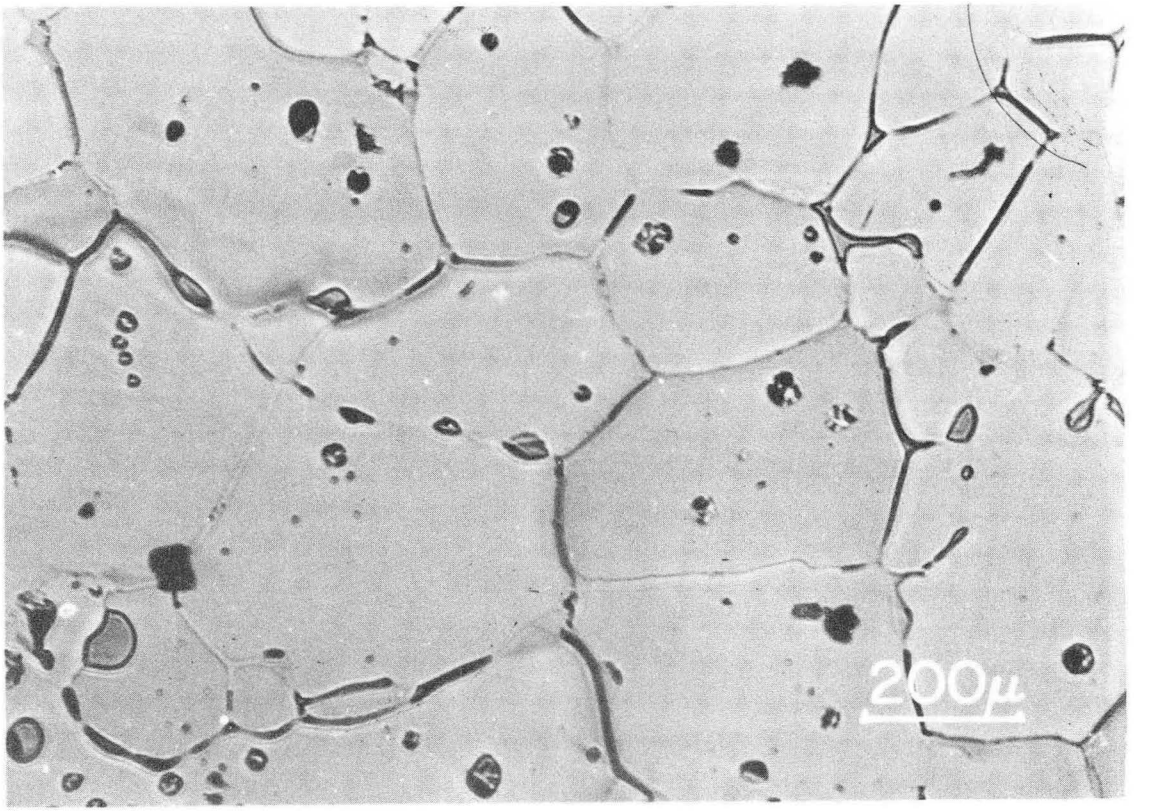
ZN-4708

Fig. 3



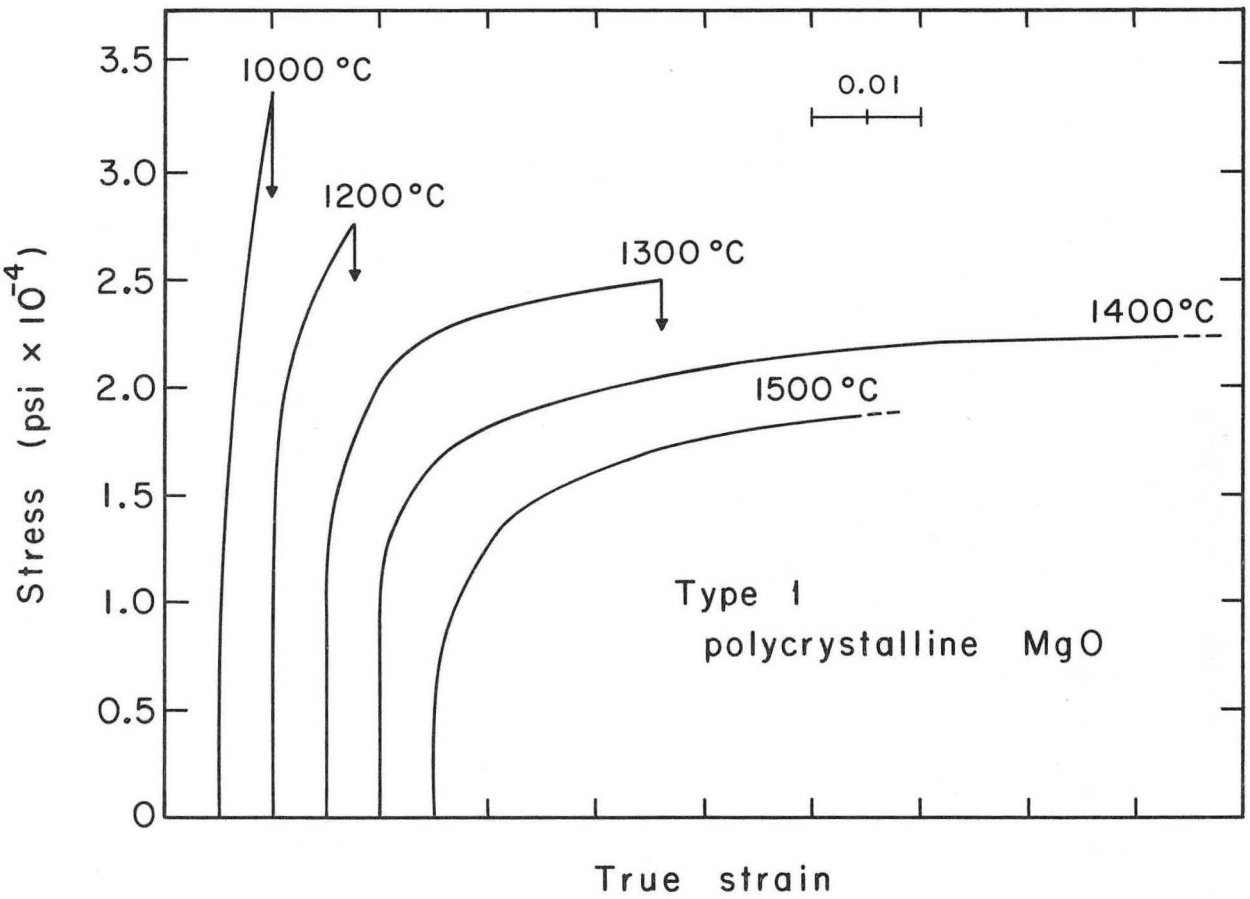
ZN-4710

Fig. 4



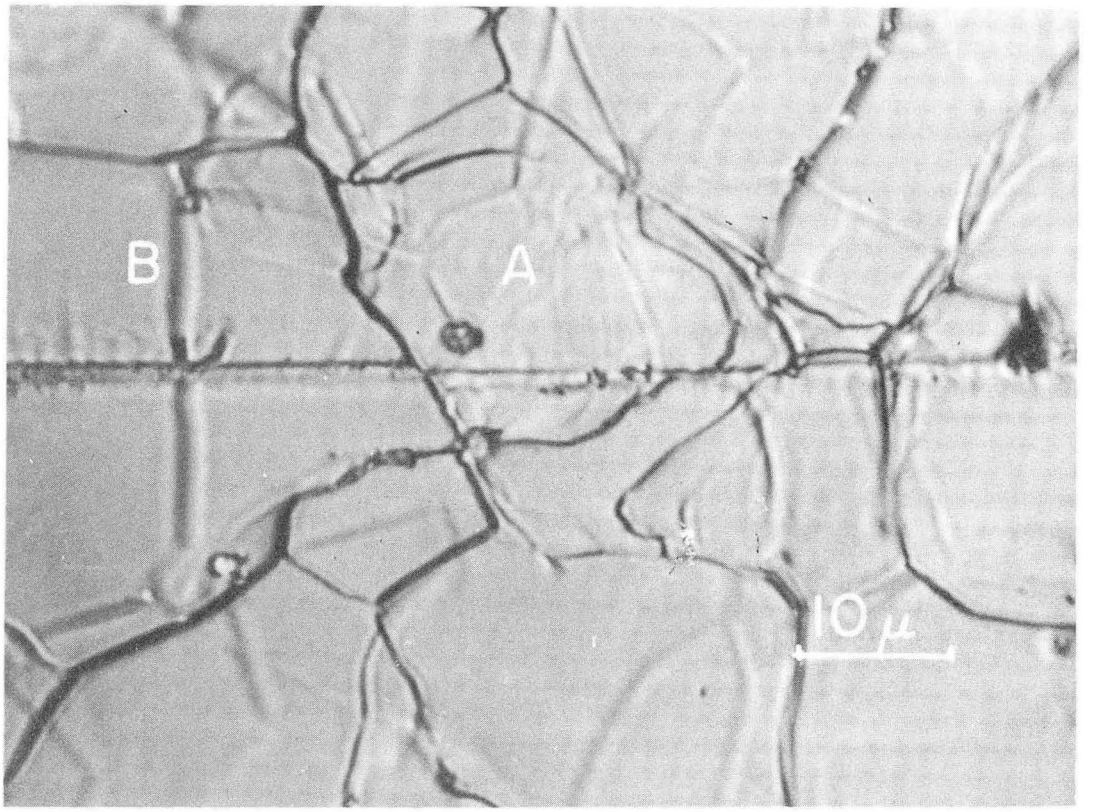
ZN-4712

Fig. 5



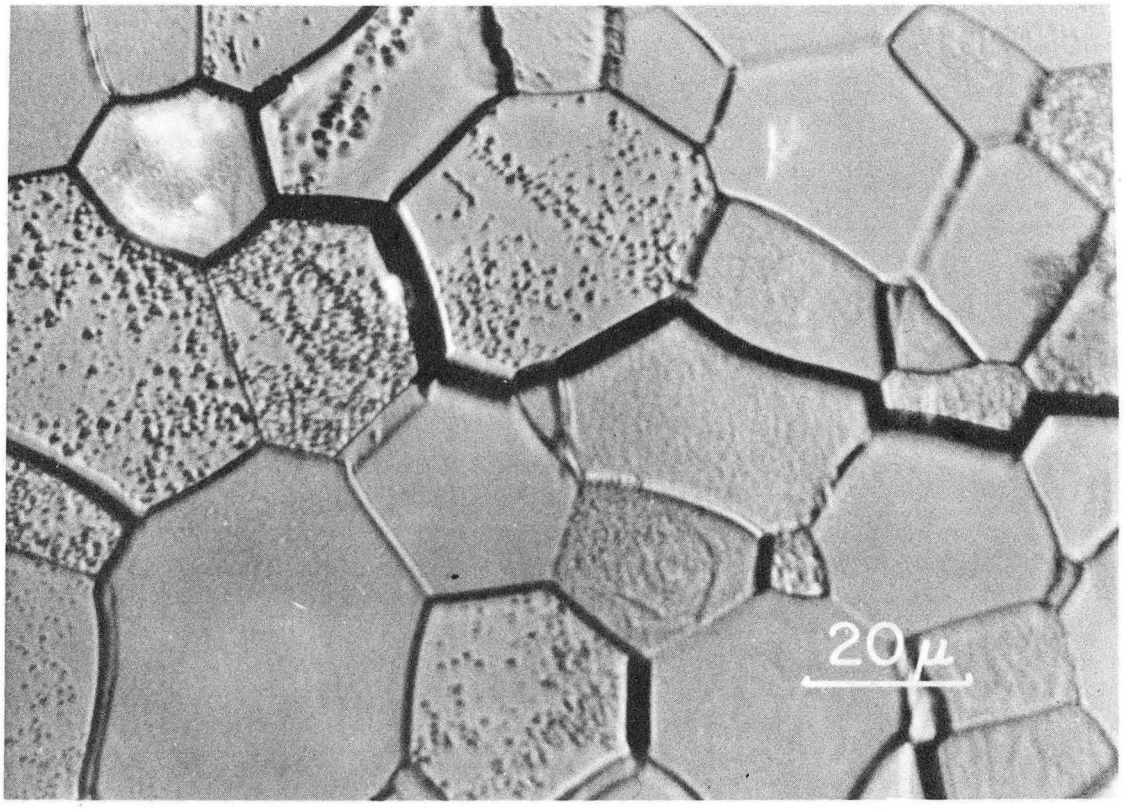
MUB-4378

Fig. 6



ZN-4707

Fig. 7



ZN-4709

Fig. 8

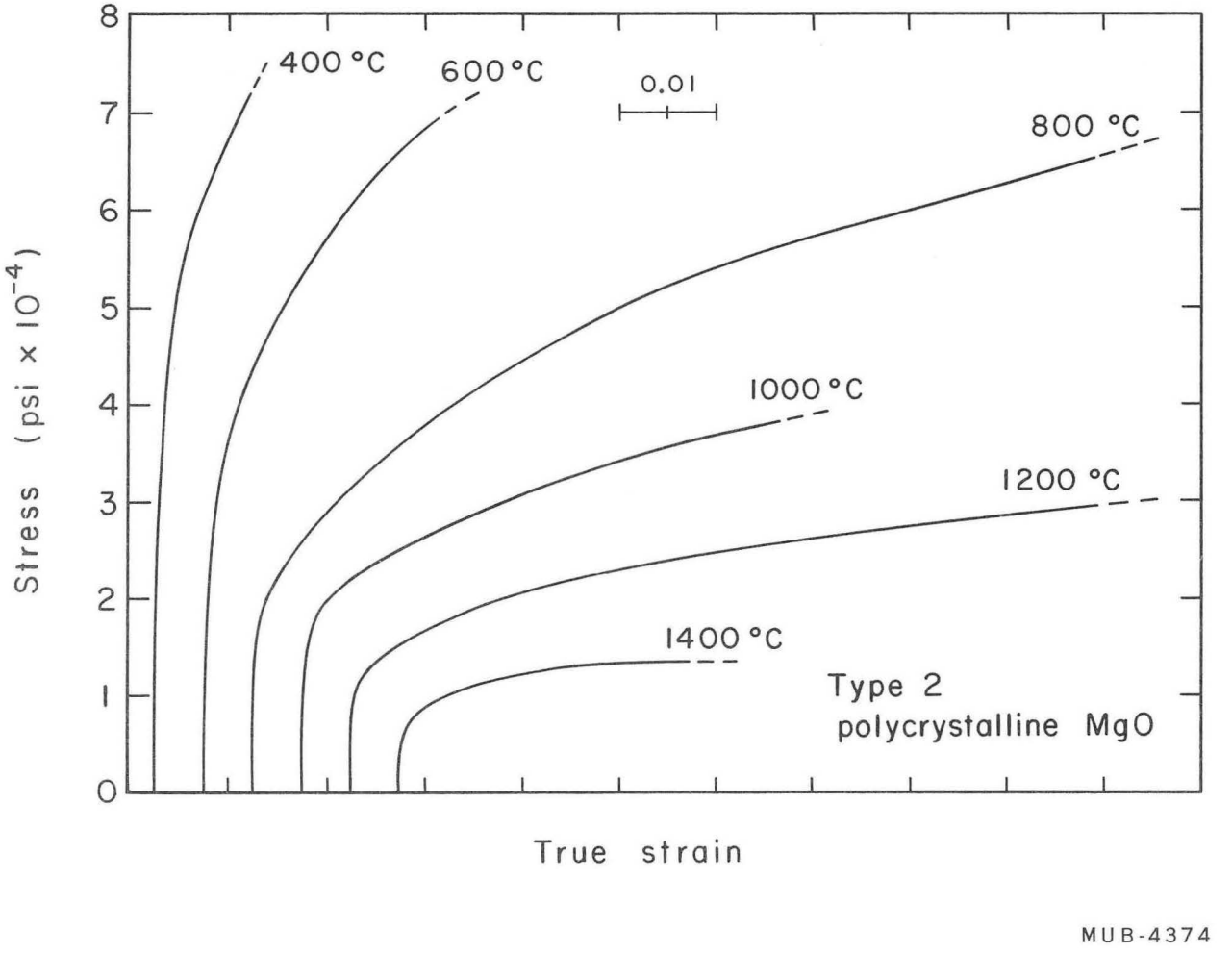
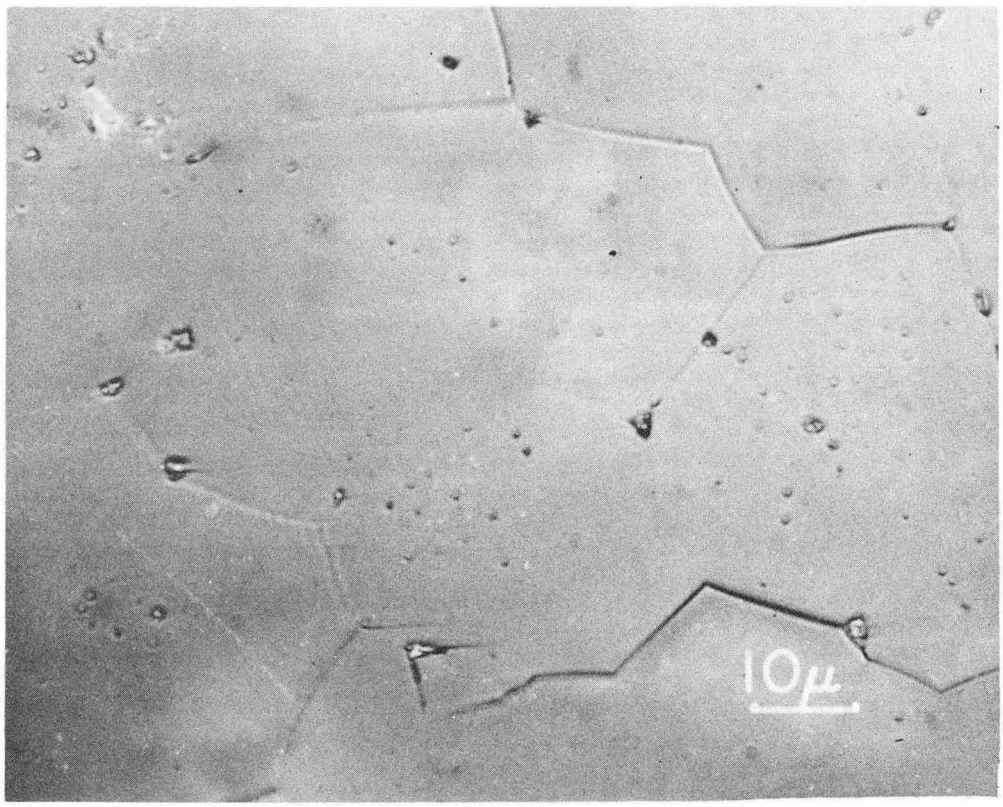
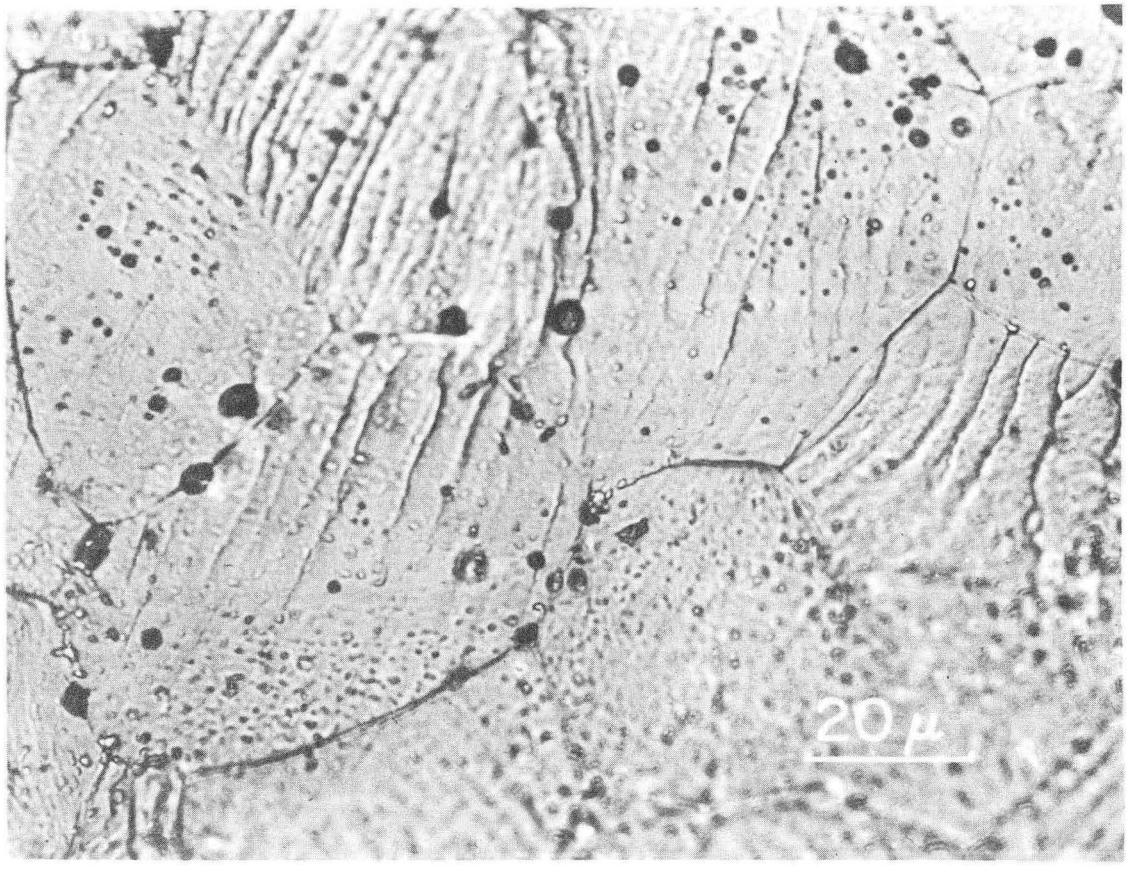

8
7
6
5
4
3
2
1
0
Stress (psi × 10^-4)
400 °C
600 °C
0.01
800 °C
1000 °C
1200 °C
1400 °C
Type 2
polycrystalline MgO
True strain
MUB-4374

Fig. 9



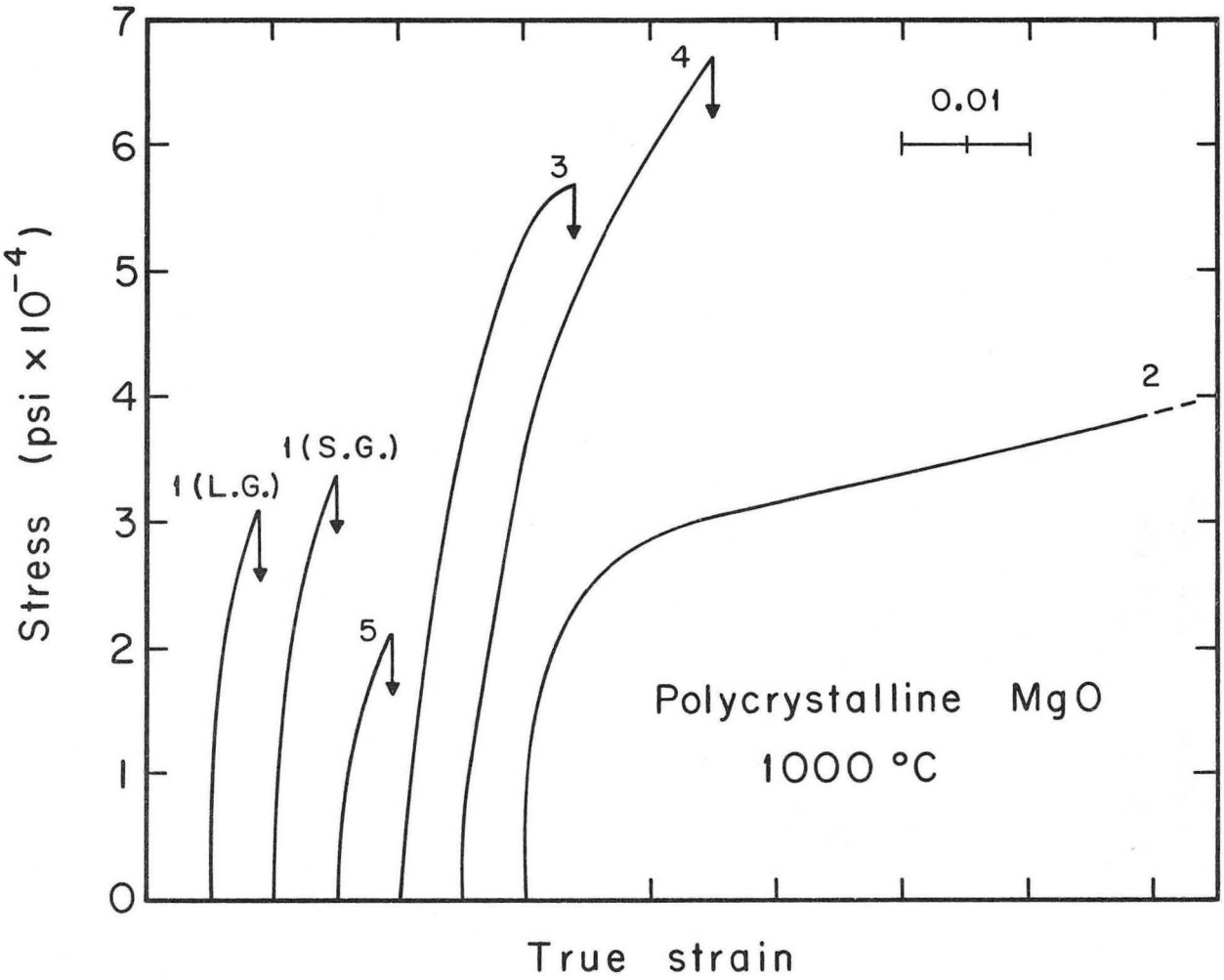
ZN-4714

Fig. 10



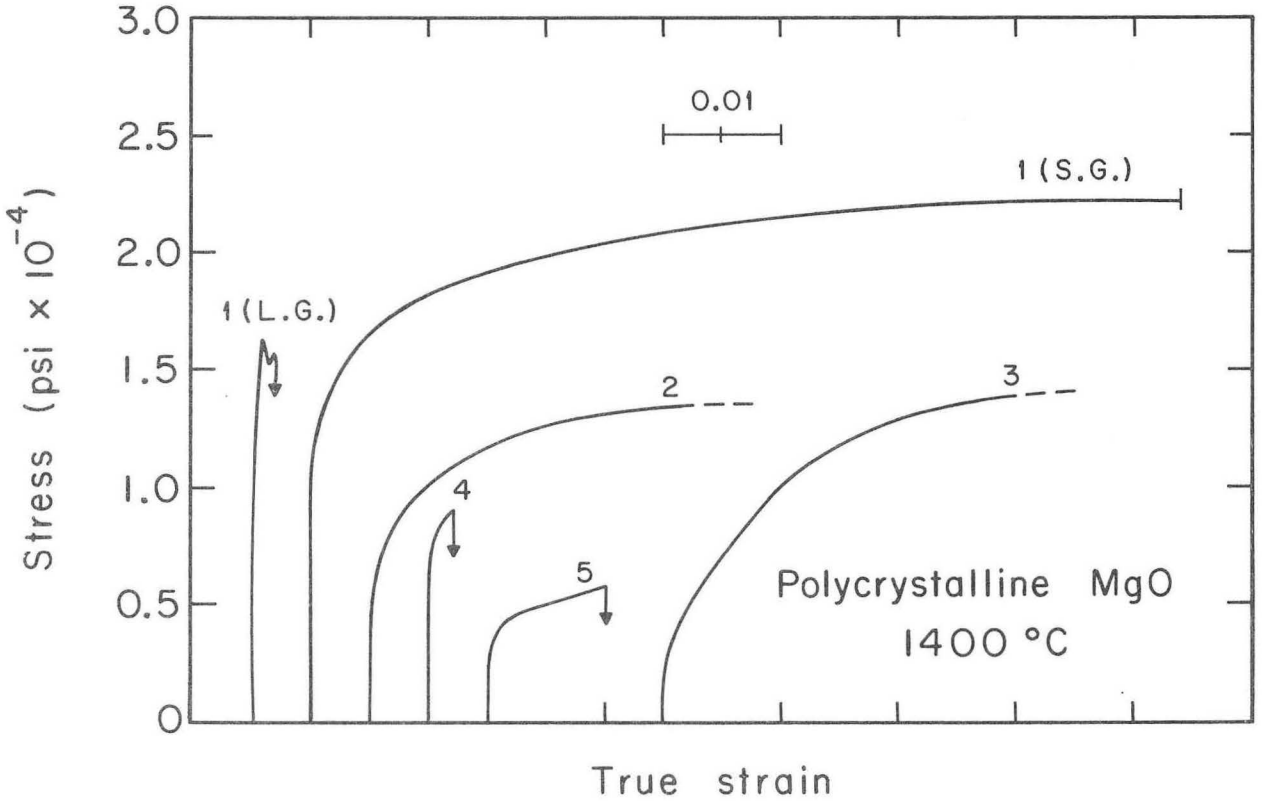
ZN-4713

Fig. 11



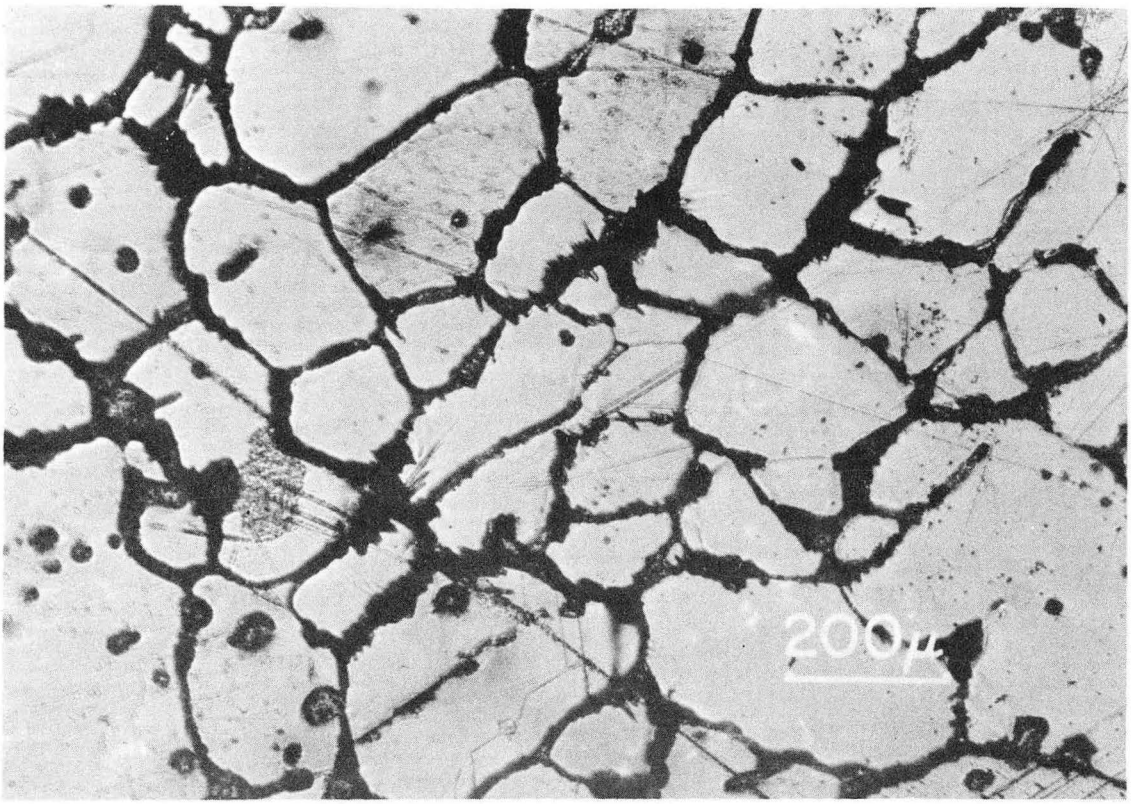
MUB-4376

Fig. 12



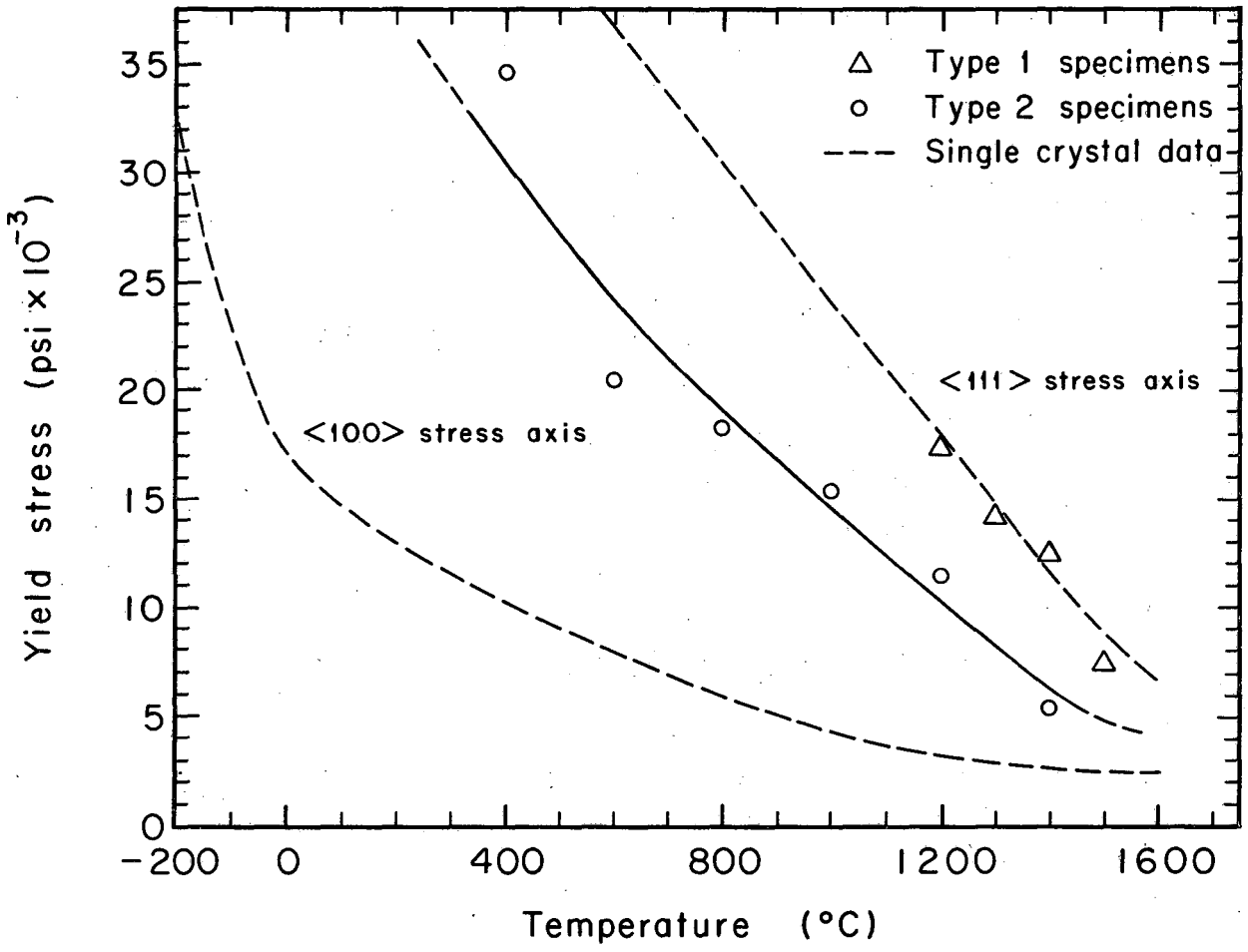
MUB-4375

Fig. 13



ZN-4715

Fig. 14



MUB-4377

Fig. 15

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