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ALLOY SOFTENING IN BINARY MOLYBDENUM ALLOYS

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ABSTRACT

An investigation was conducted to determine the effects of alloy additions of Hf, Ta, W, Re, Os, Ir, and Pt on the hardness of Mo. Special emphasis was placed on alloy softening in these binary Mo alloys. Results showed that alloy softening was produced by those elements having an excess of s+d electrons compared to Mo while those elements having an equal number or fewer s+d electrons than Mo failed to produce alloy softening. Alloy softening and alloy hardening can be correlated with the difference in number of s+d electrons of the solute element and Mo.

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SUMMARY

An investigation was conducted to determine the effects of alloy additions of Hf, Ta, W, Re, Os, Ir, and Pt on the hardness of Mo. Special emphasis was placed on alloy softening in these binary Mo alloys. A modified micro-hardness test unit permitted hardness determinations at homologous temperatures ranging from 0.02 to 0.15, where alloy softening normally occurs in b.c.c. alloys. Alloys were prepared by arc-melting high purity electron beam melted Mo and high purity alloying elements. Alloy additions ranged from less than one atom percent up to the maximum solubility of each of the elements in Mo. Hardness was determined for at least six alloys from each alloy system at four test temperatures in order to fully characterize alloy softening in these binary Mo alloys.

Results showed that alloy softening was produced by those elements having an excess of s+d electrons compared to Mo while those elements having an equal number or fewer s+d electrons than Mo failed to produce alloy softening. The magnitude of the softening and the amount of solute element at the hardness minimum diminished rapidly with increasing test temperature. At solute concentrations where alloy softening was observed, the temperature sensitivity of hardness was lowered. For solute elements having an excess of s+d electrons or fewer s+d electrons than Mo, alloy softening and alloy hardening can be correlated with the difference in number of s+d electrons of the solute element and Mo. These results point

to an intrinsic property controlling low temperature deformation of Mo alloyed with the transition elements of the sixth period.

INTRODUCTION

In a previous study (ref. 1), the authors showed that alloy softening in the Group VIA metals Cr, Mo, and W alloyed with Re was similar in all three alloy systems, occurring at homologous temperatures less than 0.16 and at Re concentrations less than 16 atom percent. The results of that study led to the conclusions that alloy softening in Group VIA-Re alloys is controlled by an inherent property and that electron concentration plays a dominant role in the hardness behavior of these alloy systems.

Alloy softening in other b.c.c. alloys continues to attract much interest on the part of numerous investigators (ref. 2). One common factor noted in these studies is that alloy systems that exhibit alloy softening also exhibit a temperature dependence of yield stress, flow stress, or hardness that is less than the solvent metal. However, investigators are not in agreement on the mechanism producing alloy softening. Especially in the Group VA metals, V, Nb, and Ta, there is disagreement on whether alloy softening results from an extrinsic factor such as scavenging of interstitial impurities or from an intrinsic factor such as lowering of the Peierls stress. For example, Hasson and Arsenault (ref. 3), using internal friction techniques, showed that in Ta+2 at.% W doped with oxygen tungsten does not act as a scavenger. The Ta-W alloy system had previously been shown to exhibit alloy softening (ref. 4). Similar results were obtained for a Ta+9.2 at.% Nb alloy doped with oxygen. In contrast, internal friction results for a V+1.31 at.% Ti alloy doped with oxygen indicated that Ti was acting as a scavenger. This was expected based on

titanium's high affinity for oxygen. Hasson and Arsenault attributed alloy softening in all three alloy systems to an intrinsic effect, lowering of the Peierls stress.

Saques and Gibala (ref. 5), using internal friction techniques, have shown that in Ta-Re-N alloys Re scavenges N and that alloy softening in this system may be due to an extrinsic factor, the Re-N interaction.

The results on Group VA metals suggest that two possible mechanisms may cause alloy softening in these metals. For the Group VIA metals the only systematic study of alloy softening is the recent investigation by the authors (ref. 1), where an intrinsic factor was postulated to be responsible for alloy softening.

The purpose of the present investigation was to further characterize alloy softening in one of the Group VIA metals, Mo, and to determine the role of electron concentration on the hardness behavior of Mo. Alloy additions included the transition metals from the sixth period, Hf, Ta, W, Re, Os, Ir, and Pt. Solute contents ranged from less than one atom percent up to the maximum solubility of solute in Mo. At least six alloys from each system were tested over a homologous temperature range of 0.02 to 0.15 utilizing a modified microhardness test unit.

SYMBOLS

a	lattice parameter
C, C_S	solute concentration
C_{Mo}	molybdenum concentration
H	hardness
VHN	Vickers hardness number
T_m	absolute melting temperature of unalloyed molybdenum

ΔF_f^o free energy of formation

ΔV change in number of s+d electrons

e/a electron-to-atom ratio

$\Omega \equiv c^{1/2}\Delta V$

EXPERIMENTAL PROCEDURE

Materials

Table I presents the nominal and analyzed compositions of unalloyed Mo and the fifty binary Mo alloys employed in this investigation. Interstitial analyses are also listed in Table I for two alloys from each alloy system. Materials used for this study included high purity electron-beam melted Mo, Ta, W, and Re; commercial purity Hf turnings and Pt foil; and hydrogen annealed Os and Ir powders. Ingots were prepared by nonconsumably triple arc-melting 70 gram charges in a water-cooled copper mold followed by drop casting into a square cross-section mold.

Slices approximately 3 mm thick by 15 mm on a side were cut from the cast ingots for hardness testing. Specimens were annealed in vacuum for one hour at 0.7 T_m or at a higher temperature within the solid solution range in order to reduce segregation and produce single phase, equiaxed, strain-free specimens. Specimens were given a metallographic polish on the face to be hardness tested.

Apparatus

The modified microhardness test unit used in this study has previously been described (ref. 1). The test unit permitted hardness testing over the temperature range 77 to 411 K.

Procedure

Alloying elements selected for this study are shown in the partial

periodic table in figure 1. Alloying elements are all from the sixth period and include the transition elements Hf through Pt. Solute contents were selected to give equivalent electron-to-atom ratios in alloys whose solute elements have fewer s+d electrons than Mo (Hf and Ta). Solute contents were similarly selected for those elements having an excess of s+d electrons compared to Mo (Re, Os, Ir, and Pt). Additions of W were excluded from this basis for alloy composition selection since Mo and W have the same number of s+d electrons. Solute contents were also chosen to cover the solubility range of each solute in Mo which can be seen in figure 2 (refs. 6-9) to vary from a minimum of only a few atom percent for Pt in Mo up to complete solubility for the Mo-Ta and Mo-W alloy systems.

Test temperatures were selected to cover approximately the temperature range where alloy softening is observed, less than 0.16 T_m for Mo-Re alloys (ref. 1), where T_m is the absolute melting temperature of unalloyed Mo. Test temperatures in equivalent increments included 77, 188, 300, and 411 K or 0.027, 0.065, 0.104, and 0.143 T_m, respectively.

A minimum of 10 diamond pyramid hardness impressions were made on each alloy at each test temperature. A load of one kilogram and a dwell time of 15 seconds were used for the impressions. Hardness readings were taken only of impressions within the grains. The relative standard deviation was 5 percent.

RESULTS

Solute Effects

As noted in figure 2, two of the sixth period elements, Ta and W, are totally soluble in Mo. The hardnesses of these two alloy systems at 300 K are included in figure 3. It should be noted that Ta additions produce

apparent parabolic hardening of Mo and that maximum hardness in this system occurs near 50 at. % Ta. In contrast W additions produce near linear hardening of Mo with hardnesses lying close to a straight line connecting the hardness values for unalloyed Mo and W.

A dramatic difference in hardness behavior is observed for alloying elements having intermediate or limited solubility in Mo. Results for Re and Pt additions from this study as well as results reported in the literature (refs. 10 to 16) are also shown in figure 3. It should be noted for Re additions at 300 K an initial softening of Mo occurs followed by apparent parabolic hardening up to the solubility limit of Re in Mo, near 40 atom percent. Formation of the σ phase produces an extremely high hardness in the Mo-Re system and finally near the Re rich end of the Mo-Re system hardness decreases to the value for unalloyed Re.

Hardness for the Mo-Pt system based on the available data from this study and data reported in the literature, apparently reaches a maximum near the maximum solubility of Pt in Mo. Within the solid solution range of Pt in Mo hardness increases rapidly with increase in Pt content.

Table II summarizes the hardness data for the seven alloy systems investigated. These data are presented graphically in figure 4. It should be noted in figure 4(a) to (c) that Hf, Ta, and W additions produce hardening of Mo over the entire homologous temperature range 0.027 to 0.143 where alloy softening was observed in Mo-Re alloys (ref. 1). In contrast, alloy additions of Re, Os, Ir, and Pt produce an initial softening of Mo at low solute contents and at low temperatures, figure 4(d) to (g). At higher solute concentrations and higher temperatures hardening of Mo is observed. The amount of solute required to produce a hardness

minimum in each of these four systems is noted (1) to increase with decreasing temperature in agreement with previous observations on Group VIA-Re alloys (ref. 1), and (2) to decrease with increasing s+d electrons.

Temperature Effects

The temperature dependence of hardness is illustrated in figure 5 for unalloyed Mo and the seven alloy systems investigated. Hardness in figure 5 is noted to decrease monotonically with temperature for unalloyed Mo and the binary Mo alloys. Examination of figure 5(c) to (g) shows that dilute additions of Re, Os, Ir, and Pt resulted in a marked decrease in the temperature dependence of hardness compared to unalloyed Mo. This decrease in temperature dependence of hardness or yield stress with alloying is characteristic of alloy softening in b.c.c. metals, having been observed in Group VIA-Re alloys by the authors (ref. 1) and in other b.c.c. metals exhibiting alloy softening (refs. 2, 4, and 5). Additions of Hf and Ta also lower the temperature sensitivity of hardness, but not sufficiently to produce softening.

DISCUSSION OF RESULTS

The purpose of this section of the report is to analyze the hardness data in terms of current theories of alloy softening and hardening and to illustrate that electron concentration plays a dominant role in the hardness behavior of binary Mo alloys.

Scavenging

The available free energies of formation ΔF_f^o (ref. 17) of the sixth period elements with C, O, and N (at 2000 K) are listed in Table III. Based on the data in Table III it is postulated that Hf and Ta would be expected to be potential scavengers of all the interstitials listed.

Comparing the values of ΔF_f^o for the oxides of the sixth period elements, those elements producing alloy hardening, Hf, Ta, and W, would be expected to scavenge oxygen from the Mo lattice. Of the elements producing alloy softening, Re, Os, Ir, and Pt, figure 4(d) to (g), only Os would be expected to scavenge oxygen from Mo. Assuming that all the oxygen in Mo is in solution and based on thermodynamic calculations, Hf at the same concentration as Os at the hardness minimum of 77 K, i.e., 1.72 at. % is calculated to be a much more effective scavenger of oxygen than Os. However, softening is not observed in Mo-Hf alloys. From these calculations the equilibrium amount of oxygen left in solution in a Mo-Hf alloy would be several orders of magnitude less than in a Mo-Os alloy.

Data are not available to make a similar comparison for carbides and nitrides, possibly because Re, Os, Ir, and Pt do not form stable carbides and nitrides.

Based on the thermodynamic calculations coupled with observations of alloy softening for Mo-Re, Os, Ir, and Pt alloys and only alloy hardening in Mo-Hf, Ta, and W alloys it is concluded that interstitial scavenging, i.e., chemical combination of solute and interstitial is not responsible for alloy softening in the binary Mo alloys under investigation.

This conclusion does not exclude the idea of solute-interstitial association proposed by Saques and Gibala (ref. 5). It is not known if this mechanism can explain the absence of alloy softening in Mo-Hf, Ta, and W alloys.

Atomic Size Misfit

It has been shown by Fleischer (ref. 18) that solution hardening can be correlated with atomic size misfit or modulus misfit factors between solute and solvent for a number of alloys of copper or silver. More

recently Mitchell and Raffo (ref. 19) have shown that the rate of alloy hardening for b.c.c. alloys is proportional to the atomic misfit parameter as measured by the rate of change in lattice parameter.

Teatum, Gschneidner, and Waber (ref. 20) have recently calculated the atomic radii for a number of solutes in Mo. The calculated atomic radius ratios of solute elements to Mo are shown in figure 6 and the change in lattice parameter of Mo upon alloying with the sixth period elements based on the data of Pearson (ref. 21 and 22) is shown in figure 7. Lattice parameter data for Mo-Pt alloys were not given by Pearson, but based upon our measurements and those of Ocken and Van Vucht (ref. 9) the lattice parameter of Mo is unchanged with additions of up to 12 atom percent Pt. Comparison of the change in lattice parameter of Mo with calculated atomic radius ratio reveals that the change in lattice parameter is as would be expected from atomic size effects. Those elements that are larger than Mo increase the lattice parameter and those that are smaller than Mo decrease the lattice parameter. The rate of increase or decrease in lattice parameter is directly proportional to the atomic radius ratio.

In figure 8(a) the initial rates of hardening for the binary Mo alloys dH/dc at 411 K from figure 4 where only hardening is observed are plotted against the initial rates of change in lattice parameter of Mo da/dc from figure 7. The data for W, Ta, and Hf additions suggest that atomic size misfit parameter may be important in controlling hardness in these systems. However, additions of Re, Os, Ir, and Pt cannot be related to atomic size misfit parameter. A similar plot is shown in figure 8(b) for data at 77 K where the initial softening rates dH/dc are shown for

Re, Os, Ir, and Pt additions along with the hardening rates for Hf, Ta, and W additions. Again hardness of binary Mo-Hf, Ta, and W alloys can be correlated with atomic size misfit parameter da/dc. Rate of alloy softening cannot be correlated with atomic size misfit for binary Mo-Re, Os, Ir, and Pt alloys.

Data for rate of change in modulii are not available for the binary alloys and, therefore, the correlation with rate of hardening or softening cannot be examined.

Electron Concentration

A further comparison is made of the hardness behavior of the binary Mo alloys for data determined at 77 K. In figure 9(a) data are compared for those alloys producing hardening of Mo while in figure 9(b) a comparison is made of data for alloying elements that initially produce softening of Mo. The increases in hardness at a particular solute content are noted to vary remarkably. For example, at a solute content of 8 atom percent for solute elements producing only hardening of Mo, figure 9(a) approximate increases in VHN of 30, 80, and 160 result for alloy additions of W, Ta, and Hf respectively. In contrast, at a similar solute contents for those elements producing an initial softening of Mo, figure 9(b), increases in VHN of approximately 160, 380, and 620 result for additions of Os, Ir, and Pt while Re additions at the 8 atom percent produce a decrease in VHN of approximately 75, as shown in figure 9(b).

It was mentioned previously in the Experimental Procedure that solute content was selected to give alloys having equivalent electron-to-atom ratios, e/a. The e/a ratio of binary Mo alloy can be represented by

$$(e/a)_{alloy} = [C_{Mo}(e/a)_{Mo} + C_S(e/a)_S] \qquad (1)$$

where C_{Mo} and C_S are the atom fraction of Mo and solute, respectively. Equation (1) can be written as

$$(e/a)_{alloy} = (1-C_S)\,(e/a)_{Mo} + C_S(e/a)_S \qquad (2)$$

or

$$(e/a)_{alloy} = (e/a)_{Mo} + C_S\,[(e/a)_S - (e/a)_{Mo}] \qquad (3)$$

where $[(e/a)_S - (e/a)_{Mo}]$ is equal to the change in number of s + d electrons (ΔV).

The change in electron concentration upon alloying Mo with elements from the sixth period is given by

$$\Delta\, e/a = (e/a)_{alloy} - (e/a)_{Mo} = C_S\,\Delta V \qquad (4)$$

Values of number of s+d electrons are shown in figure 1.

The effect of change in electron concentration on hardness for the binary Mo alloys is shown in figure 10 for data determined at 77 K. Data for Mo-W alloys are excluded from this plot since $\Delta V = 0$. It is interesting to note in figure 10 that a smooth curve can be drawn through hardness values for dilute Mo-Hf and Mo-Ta alloys where hardening is observed and hardness values for dilute Mo-Re, Os, Ir, and Pt alloys where alloy softening is observed. The authors (ref. 1) showed that alloy hardening in Group VIA-Re alloys was proportional to the square root of solute content (parabolic hardening). Figure 11 shows the variation of hardness with square root of solute content and the change in electron concentration where the parameter Ω, is

$$\Omega \equiv C^{1/2}\,\Delta V$$

It can be seen in figure 11(a) that the alloy hardening data at 77 K for Mo-Hf and Mo-Ta alloys and alloy softening data for Mo-Re, Os, Ir, and Pt alloys also yields a reasonable fit of the data with the exception of the two most concentrated Mo-Re alloys. Figure 11(b), (c), and (d) shows that this type of correlation of the data is satisfactory at temperatures of 188, 300, and 411 K. It should be noted in figure 11 that the slopes of the two lines are approaching each other as temperature increases, implying that hardness can be correlated with $|\Delta V|$ above the temperature where alloy softening disappears.

From the correlation shown in figure 11 it is concluded that the hardness or strength of binary alloys of Mo - sixth period elements Hf through Pt can best be correlated with electron concentration. Even though the initial rate of hardening in Mo-Hf and Mo-Ta alloys could be correlated with atomic size factor it appears that electron concentration plays a more dominant role over the entire range of compositions investigated here.

Comparison of our previous work on Group VIA-Re alloys (ref. 1) reveals that a correlation of hardness for these alloys is also consistent with the present relation between hardness and Ω, since for Cr, Mo, or W alloyed with Re ΔV is constant. A least squares fit of hardness data in the previous study indicated hardness could be expressed proportional to Re content or to the square root of Re content. Based on the present results it appears that the square root of solute content is preferred. It would appear from these two studies that the correlation between electron concentration and hardness or strength may be applicable to other b.c.c. transition metal alloys.

Examination of figure 11 reveals that the hardness minimum occurs at lower values of Ω with increasing temperature. Figure 12 shows that Ω_{Min}, the value of Ω at the hardness minimum, decreases linearly with increasing temperature. A least squares line through the data in figure 12 extrapolates to a temperature of 487 K (0.169 Tm). Above this temperature alloy softening would not be expected in the binary Mo-sixth period element alloys. This is in good agreement with a temperature of 461 K (0.16 Tm) for Mo-Re alloys determined by averaging the data for Group VIA-Re alloys (ref. 1). The line in figure 12 extrapolates to Ω_{Min} = 3.17 (at. %)$^{1/2}$ at 0 K from which the maximum amount of solute that can be added to produce alloy softening can be determined from the relation

$$\Omega_{Min} = C^{1/2}\,\Delta V = 3.17\ (\text{at. }\%)^{1/2} \text{ at } 0\ \text{K}.$$

The amounts of Re, Os, Ir, and Pt expected at the hardness minimum in Mo would be 10, 2.5, 1.1, and 0.6 atom percent, respectively.

CONTROLLING MECHANISM

The correlation of hardness with electron concentration for the alloys investigated points to an intrinsic property of the transition metal alloys being responsible for the alloy softening and hardening that has been observed in this study. The lack of softening in Mo-Hf and Ta alloys suggests that scavenging, even though it may occur in these alloys is not important in controlling alloy softening in these materials. Also, failure to correlate hardening or softening rates with atomic size factor alone, especially where the greatest rates of hardening and softening were observed in Mo-Pt alloys without a change in lattice parameter, precludes atomic size factor being a controlling mechanism. As pointed out

previously by the authors (ref. 1) and by Arsenault (ref. 23), alloying Mo with elements having a greater number of s+d electrons can lead to a reduction in the Peierls stress as a result of reducing the directionality of the electron bonding. A lowering of the Peierls stress has been proposed by several investigators to be responsible for alloy softening (refs. 1, 2, 3, 18, and 22).

The abrupt change to alloy hardening at $\Omega = 2.64$ (at. %)$^{1/2}$ at 77 K for the binary Mo alloys and at decreasing Ω at higher temperatures is of primary importance in determining the mechanism of alloy softening and hardening in these alloys. Some insight into the change in softening to hardening at these e/a ratios may be gained from a study of the magnetic susceptibility of these alloys which gives some information as to the electron structure. Jones and McQuillan (ref. 24) and Booth (ref. 25), in studying the magnetic susceptibility of Mo-Re alloys, showed that instead of the expected increase in magnetic susceptibility with increase in Re content within the entire solubility range a maximum was observed. Jones and McQuillan or Booth did not correlate this anomaly with the density-of-states curve, but if the observation is real and characteristic of the other binary Mo alloys under investigation here, measurements of this type may help lead to an understanding of the role that electron structure plays in the mechanical behavior of the transition metals and alloys.

CONCLUSIONS

Based on a hardness study of binary Mo-Hf, Ta, W, Re, Os, Ir, and Pt alloys the following conclusions are drawn:

1. Hardness of the alloys investigated can be correlated with

electron concentration of the alloys.

2. Alloy softening is produced in Mo by those elements having an excess of s+d electrons compared to Mo. Elements having fewer s+d electrons than Mo or an equal number of s+d electrons do not produce alloy softening.

3. Alloy hardening of Mo-Hf and Mo-Ta alloys and alloy softening of Mo-Re, Os, Ir, and Pt alloys can be correlated with the square root of solute content and change in electron concentration due to addition of the solute element. Alloy hardening in Mo-Re, Os, Ir, and Pt alloys obeys a similar correlation.

4. Scavenging of interstitials by solute elements does not appear responsible for alloy softening in Mo-sixth period transition metal alloys.

5. Atomic size factor may play a minor role in hardness behavior of Mo-Hf, Ta, and W alloys, but cannot be correlated with hardness behavior of Mo-Re, Os, Ir, and Pt alloys.

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TABLE I

CHEMICAL ANALYSIS, ELECTRON-TO-ATOM RATIO AND VALUES OF Ω FOR BINARY Mo ALLOYS

[Solute Content (at. %). Interstitial Content (wt-ppm).]

(a) Mo-Hf Alloy System

Nominal	Analyzed	C	H	N	O	e/a	$\Omega=C^{1/2}\ \Delta V$
1.0	0.92					5.982	-1.92
2.5	2.7	16	2.0	2.1	29	5.946	-3.29
4.0	3.9					5.922	-3.95
5.0	4.8					5.904	-4.38
10.0	9.9	21	2.2	4.2	31	5.802	-6.29
16.0	15.9					5.682	-7.98

(b) Mo-Ta Alloy System

0.4	0.23					5.998	-0.45
2.0	2.2	13	2.5	3.4	16	5.978	-1.48
5.0	4.9					5.951	-2.21
8.0	7.9					5.921	-2.81
20.0	17.1	12	2.5	4.9	40	5.829	-4.14
32.0	25.3					5.747	-5.03
40.0	38.2					5.618	-6.18
60.0	59.3					5.407	-7.71
80.0	81.5					5.185	-9.04

(c) Mo-W Alloy System

Nominal	Analyzed	C	H	N	O	e/a	$\Omega=C^{1/2}\ \Delta V$
2.0	1.1					6.00	0
5.0	3.4	25	2.7	4.0	24		
8.0	5.5						
10.0	12.1						
20.0	18.8	8	1.4	1.6	17		
32.0	37.2						
60.0	58.3						
80.0	82.4						

(d) Mo-Re Alloy System

2.0	2.0	31	2.1	4.1	24	6.020	1.41
5.0	5.3					6.053	2.30
8.0	8.2					6.082	2.86
10.0	10.2					6.102	3.19
20.0	20.3	41	1.6	6.5	29	6.203	4.51
32.0	32.6					6.326	5.71

(e) Mo-Os Alloy System

1.0	1.11					6.022	2.10
1.7	1.72					6.034	2.63
2.5	2.61	12	1.8	2.2	20	6.052	3.24
4.0	3.64					6.073	3.82
5.0	5.23					6.105	4.57
10.0	9.85	19	3.4	3.2	20	6.197	6.28
16.0	15.76					6.315	7.94

(f) Mo-Ir Alloy System

Nominal	Analyzed	C	H	N	O	e/a	$\Omega=C^{1/2}\ \Delta V$
0.67	0.63					6.019	2.39
1.10	1.12					6.034	3.18
1.67	1.71					6.051	3.92
2.67	2.49	16	1.1	7.7	20	6.075	4.73
3.30	3.31					6.099	5.46
6.67	6.76	15	3.0	3.7	41	6.203	7.80
10.67	10.46					6.314	9.70

(g) Mo-Pt Alloy System

0.5	0.20					6.008	1.79
0.75	0.71					6.028	3.38
1.0	1.2					6.048	4.38
2.0	2.0	14	2.3	2.3	23	6.080	5.66
2.5	2.5					6.100	6.32
5.0	4.8					6.192	8.76
8.0	7.6					6.304	11.03

(h) Mo

-	-	15	1.4	3.4	20	6.000	0

TABLE II

SUMMARY OF HARDNESS DATA FOR BINARY Mo ALLOYS

(a) Mo-Hf alloy system

Hf content, at. %	Temperature, K 77	188	300	411
	Hardness, VHN			
0.92	421	290	190	159
2.7	437	312	251	221
3.9	455	345	301	266
4.8	490	355	318	278
9.9	601	494	450	392
15.9	689	624	576	567

(b) Mo-Ta alloy system

Ta content, at. %				
0.23	414	280	175	104
2.2	418	299	186	127
4.9	443	333	216	173
7.9	472	347	246	214
17.1	524	416	341	308
25.3	557	458	397	357
38.2	531	485	427	389
59.3	513	470	418	400
81.5	436	359	309	280

(c) Mo-W alloy system

W content, at. %	Temperature, K 77	188	300	411
	Hardness, VHN			
1.1	401	281	169	110
3.4	405	277	177	105
5.5	423	292	179	117
12.1	429	304	186	123
18.8	462	325	201	140
37.2	508	347	228	162
58.3	550	414	287	200
82.4	627	473	343	237

(d) Mo-Re alloy system

Re content, at. %				
2.0	375	258	150	113
5.3	332	226	158	144
8.2	315	238	189	166
10.2	336	249	202	179
20.3	383	326	267	235
32.6	438	393	332	293

(e) Mo-Os alloy system

Os content, at. %				
1.11	349	237	172	149
1.72	335	263	218	185
2.61	375	303	250	218
3.64	414	346	307	263

(e) Mo-Os alloy system (continued)

Os content, at. %	Temperature, K 77	188	300	411
	Hardness, VHN			
5.23	452	370	318	297
9.85	600	524	461	407
15.76	716	615	555	486
(f) Mo-Ir alloy system				
Ir content, at. %				
0.63	350	267	212	184
1.12	405	334	267	232
1.71	453	376	296	282
2.49	520	472	389	339
3.31	567	512	439	379
6.76	730	660	609	549
10.46	805	731	711	682
(g) Mo-Pt alloy system				
Pt content, at. %				
0.20	368	241	171	139
0.71	401	330	254	227
1.2	475	412	315	295
2.0	513	470	393	383
2.5	592	544	476	435
4.8	830	757	674	619
7.6	976	949	855	779
(h) Mo				
	391	267	171	105

TABLE III

FREE ENERGIES OF FORMATION ΔF_f° AT 2000 K FOR SOLUTE-INTERSTITIAL REACTIONS (Ref. 17)

Element	Interstitial					
	C		O		N	
	Compound and ΔF_f°, kilojoule/gram-atom of interstitial					
Hf	HfC	-208.8	HfO_2	-376.6	HfN	-184.5
Ta	Ta_2C	-187.9	Ta_2O_5	-240.2	Ta_2N	-118.8
W	W_2C	-116.3	WO_2	-120.9	-	
Re	-		ReO(g)	178.2	-	
Os	-		OsO_3(g)	-60.2	-	
Ir	-		IrO(g)	241.4	-	
Pt	-		PtO(g)	172.0	-	
Mo	Mo_2C	-63.6	MoO_2	-121.3	-	

	GROUP IV	GROUP V	GROUP VI	GROUP VII	GROUP VIII		
FIFTH PERIOD			42 Mo 95.94				
SIXTH PERIOD	72 Hf 178.49	73 Ta 180.94	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09
NUMBER OF s AND d ELECTRONS	4	5	6	7	8	9	10

Figure 1. - Partial periodic table showing solute elements alloyed with molybdenum for this investigation.

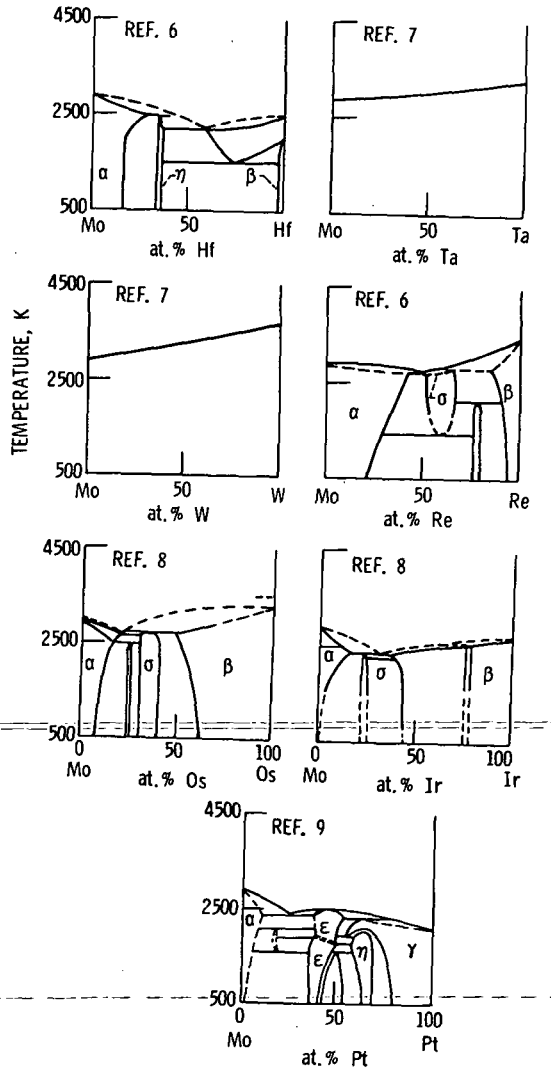


Figure 2. - Equilibrium diagrams for binary molybdenum alloy systems under investigation.

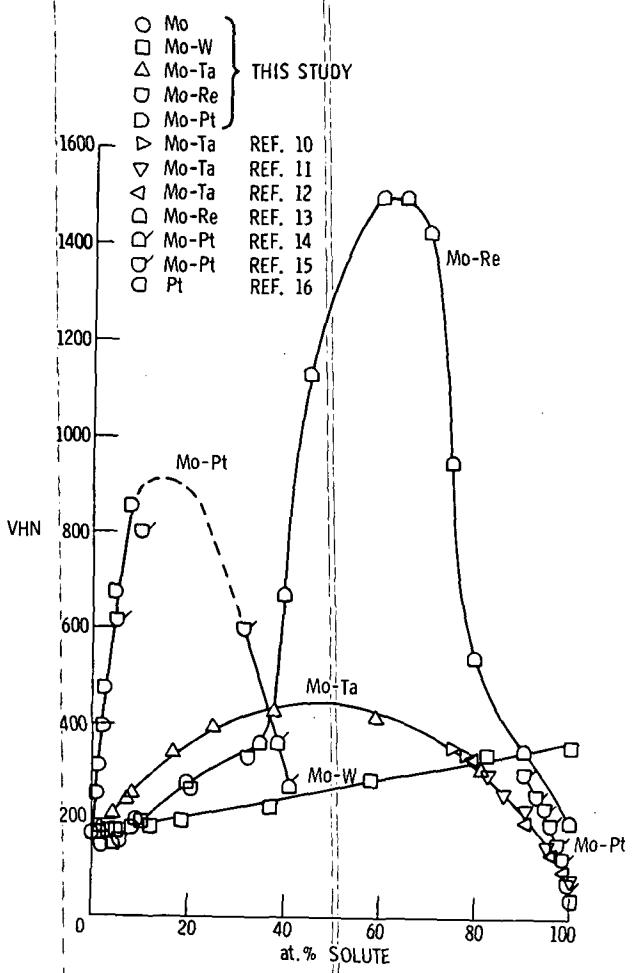
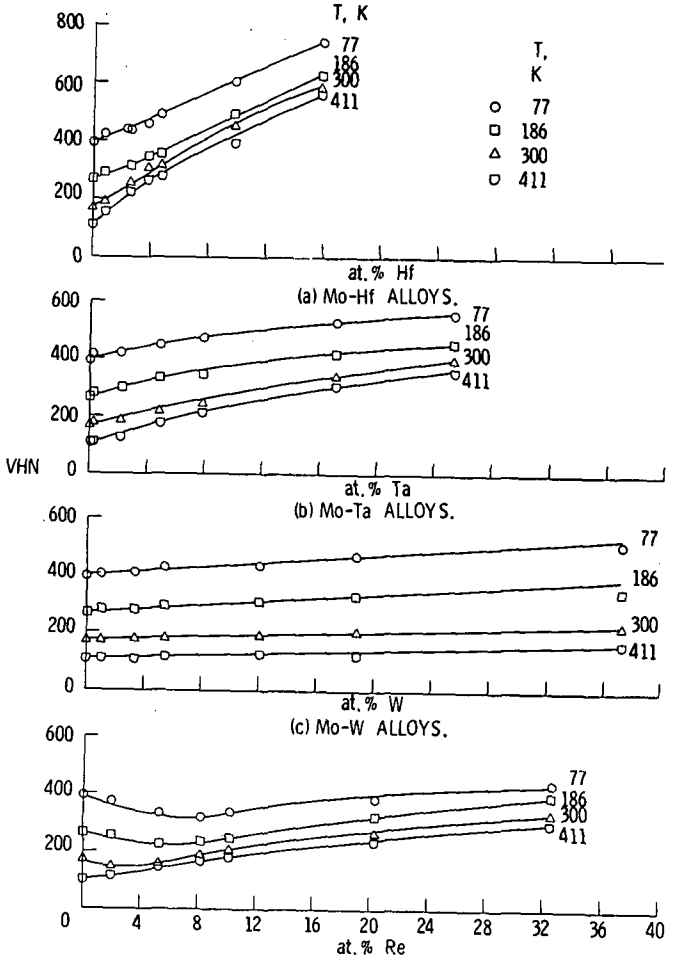
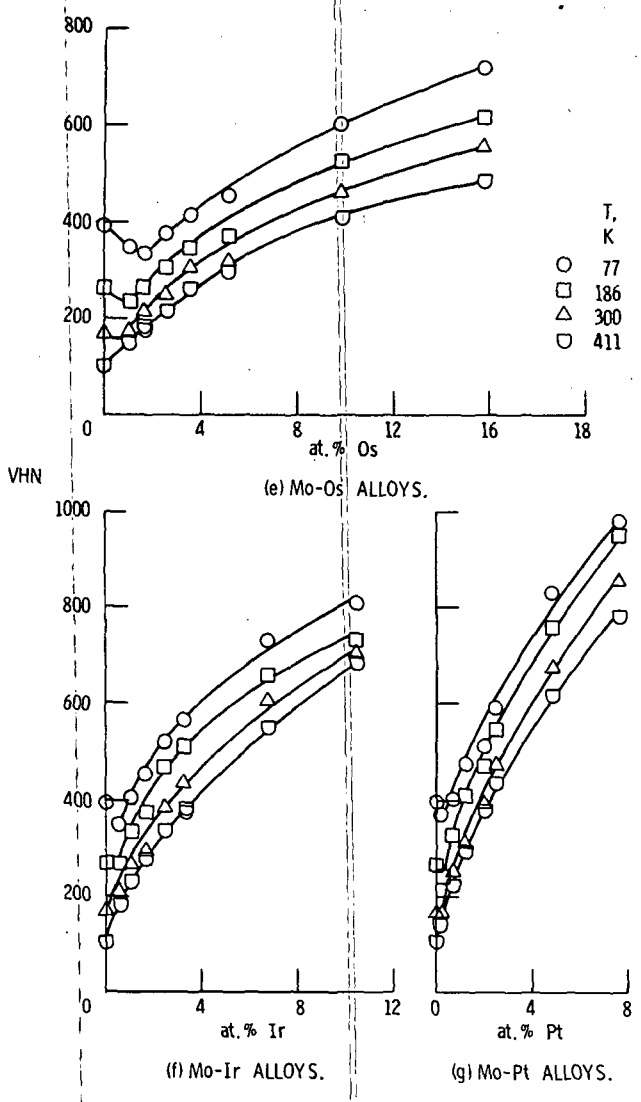


Figure 3. - Hardness behavior at 300 K in the Mo-W, Ta, Re, and Pt alloy systems.



(d) Mo-Re ALLOYS.

Figure 4. - Effect of solute content on hardness of Mo.

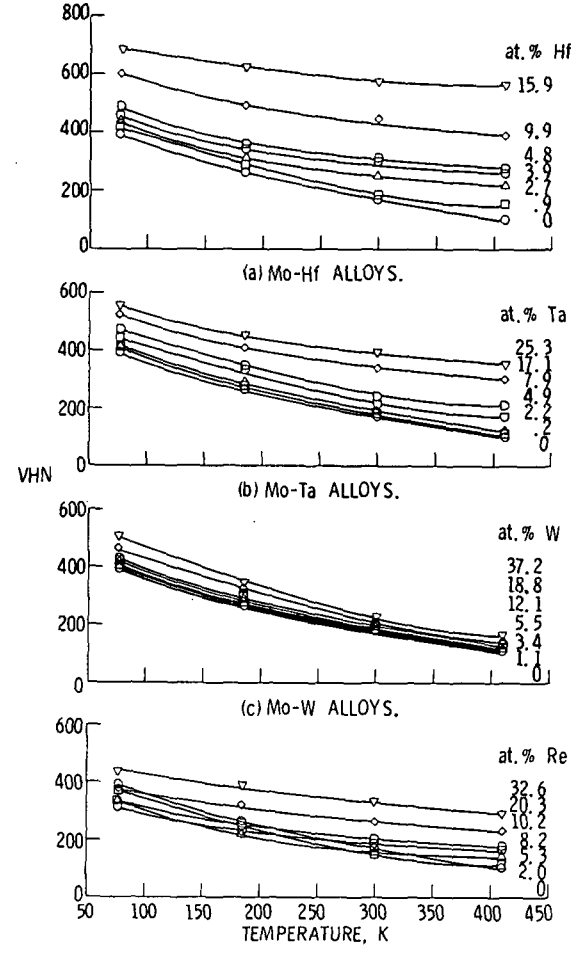


(e) Mo-Os ALLOYS.

(f) Mo-Ir ALLOYS.

(g) Mo-Pt ALLOYS.

Figure 4. - Concluded.



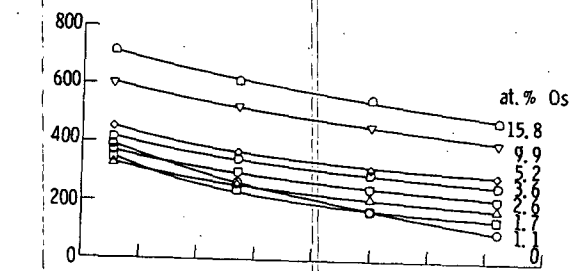
(a) Mo-Hf ALLOYS.

(b) Mo-Ta ALLOYS.

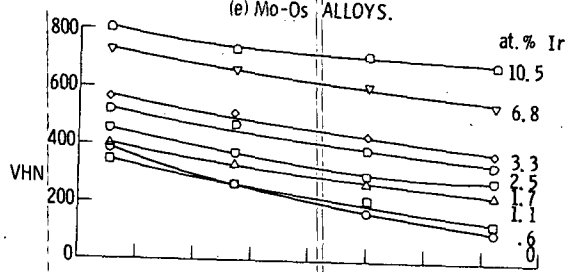
(c) Mo-W ALLOYS.

(d) Mo-Re ALLOYS.

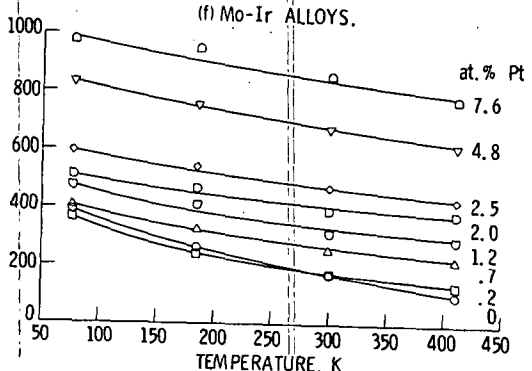
Figure 5. - Effect of temperature on hardness of binary Mo alloys.



(e) Mo-Os ALLOYS.



(f) Mo-Ir ALLOYS.



(g) Mo-Pt ALLOYS.

Figure 5. - Concluded.

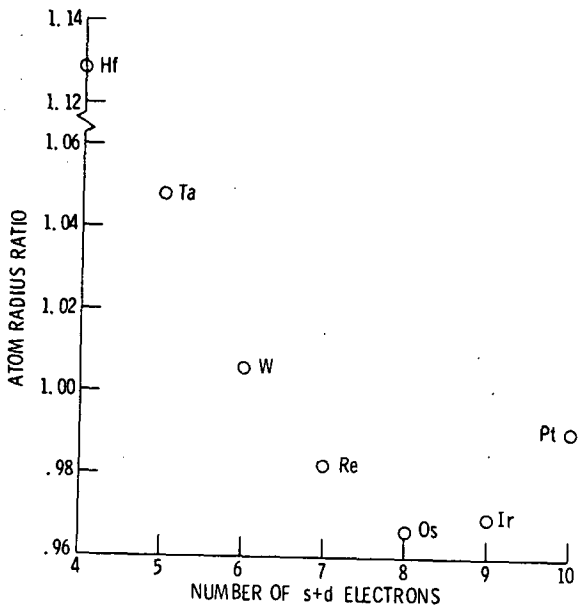


Figure 6. - Comparison of calculated solute solvent atom radius ratios for binary Mo alloys (ref. 20).

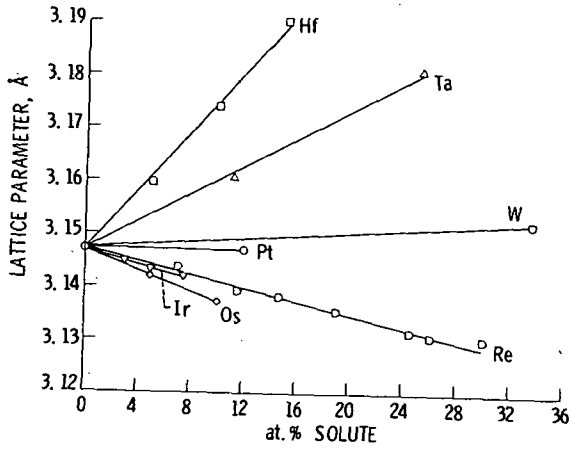


Figure 7. - Lattice parameters of binary Mo alloys as a function of solute content (refs. 9, 21, and 22).

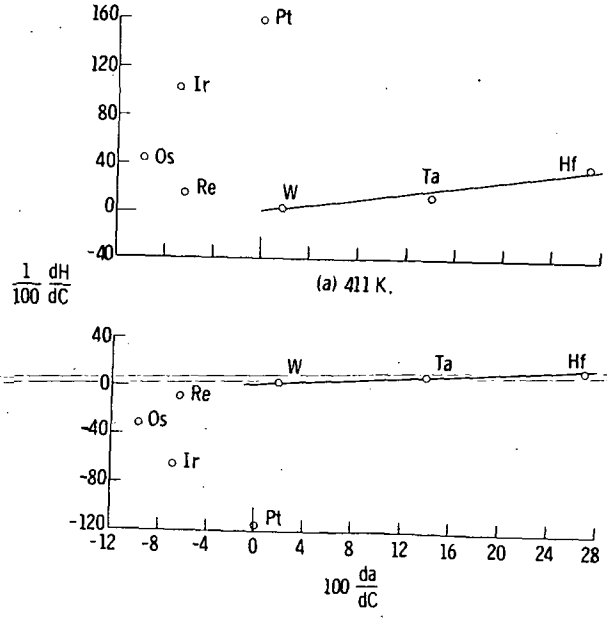
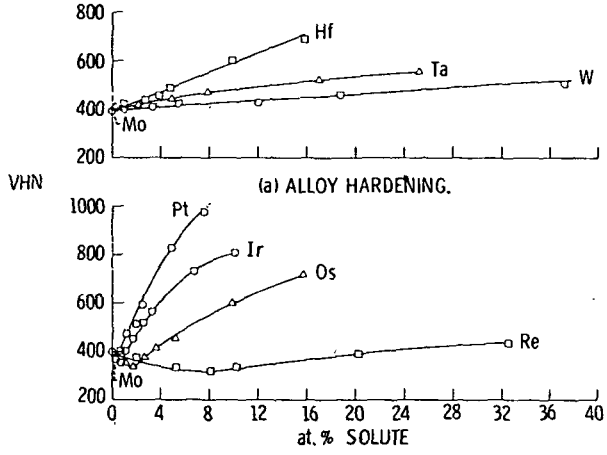


Figure 8. - Effect of atomic size factor on hardening and softening rates in binary Mo alloys.



(b) ALLOY SOFTENING AND ALLOY HARDENING.

Figure 9. - Comparison of hardness behavior of binary Mo alloys at 77 K.

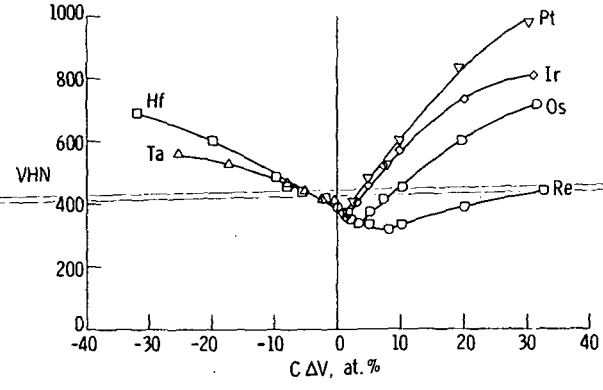
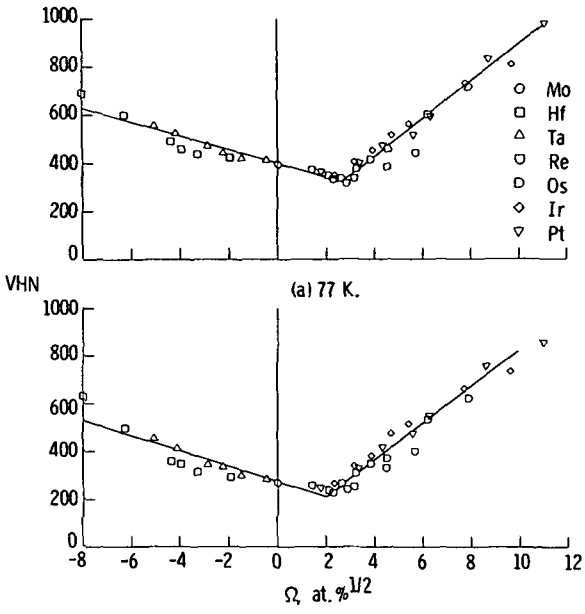
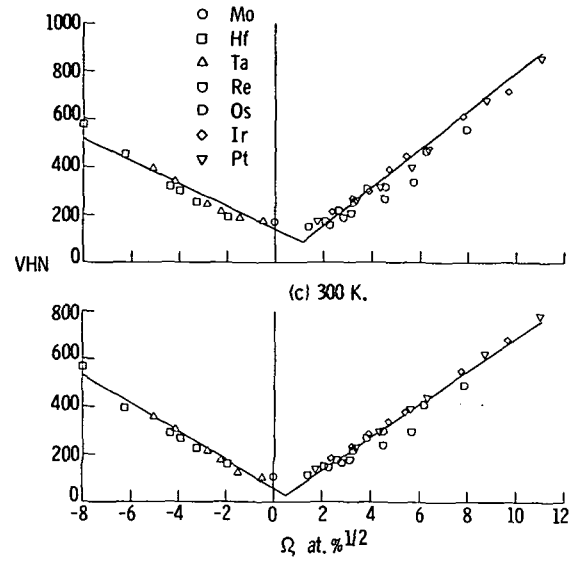


Figure 10. - Effect of solute content and change in electron concentration on hardness of binary Mo alloys at 77 K.



(b) 188 K.

Figure 11. - Effect of square root of solute content and change in electron concentration on hardness of binary Mo alloys.



(d) 411 K.

Figure 11. - Concluded.

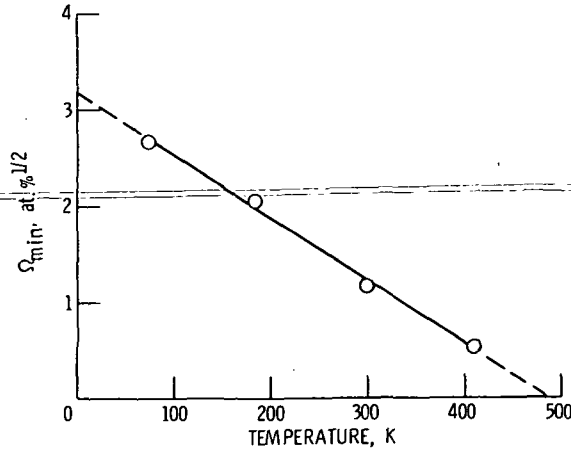


Figure 12. - Temperature dependency of Ω_{min}.