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ALLOY SOFTENING IN GROUP VIA METALS ALLOYED WITH RHENIUM

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16. Abstract
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SUMMARY

An investigation was conducted to determine the effects of temperature and composition on alloy softening in group VIA metals chrominum, molybdenum, and tungsten alloyed with rhenium. Microhardness measurements were made at homologous temperatures from 0.02 to 0.2, the range where alloy softening is normally observed in bcc alloys. Rhenium contents ranged from zero up to the maximum solubility of Re in each of the group VIA metals. Hardness was measured for approximately 14 alloys from each system at six test temperatures in order to adequately describe alloy softening in group VIA-Re alloys.

Results showed that alloy softening was similar in all three alloy systems, occurring at homologous temperatures less than 0.16 and at rhenium concentrations less than 16 atom percent. The rhenium content required to produce a hardness minimum diminished rapidly in all three systems with increasing test temperature. A sharp temperature dependence of hardness was observed in dilute alloys that exhibited alloy softening. Alloy hardening was observed in concentrated alloys at all temperatures and in dilute alloys at homologous temperatures greater than 0.16. A much lower temperature dependence of hardness was observed for these alloys. The conditions under which both alloy softening and alloy hardening occur can be expressed empirically in terms of rhenium content and temperature. The similarities in hardness behavior in these alloy systems suggest a common softening mechanism. Lowering of the Peierls stress as a result of rhenium changing the electron structure is believed to be the operative mechanism.

INTRODUCTION

The phenomenon of alloy softening observed in body-centered-cubic (bcc) alloys at low temperatures and at low alloy concentrations is now considered to be the rule rather than the exception. For example, alloy softening has been observed in bcc iron by Christ, Gamble, and Smith (ref. 1), in the group VA metals vanadium (Keith, ref. 2), niobium (Harris ref. 3), in tantalum (Mitchell and Raffo ref. 4), and in group VIA metals chromium (Allen and Jaffee ref. 5), molybenum (Lawley and Maddin ref. 6), and tungsten (Pugh, Amra, and Hurd ref. 7). From the accumulated data it is evident that both interstitial and substitutional solutes can produce alloy softening in bcc metals. For example, alloy softening is observed in iron as a result of nitrogen or nickel additions (ref. 1) and in tantalum as a result of oxygen additions (ref. 8) or rhenium additions (ref. 4).

Alloy softening has been observed in bcc metals only at temperatures less than 0.2 T_m, the temperature range where a rapid increase in flow stress with decreasing temperature normally occurs for the unalloyed metals. Investigators are not in agreement as to the mechanism that produces alloy softening. Two explanations that have received the most consideration are (1) lowering the Peierls stress, which is assumed to be high for bcc metals and (2) scavenging of interstitial impurities.

The previous studies have identified numerous solute additions which produce alloy softening in bcc metals, but, because of the limited number of tests conducted, these studies have not determined the combinations of solute content and temperature under which alloy softening can be expected. Hardness testing provides a simple and expedient method of determining an indication of mechanical properties of metals and only a small amount of material is needed to characterize an alloy system over a wide range of temperature and composition.

The purpose of this investigation was to determine the effects of temperature and composition on alloy softening in the group VIA metals chromium, molybdenum, and tungsten alloyed with rhenium. These alloy systems are of particular interest because of the associated beneficial effect of rhenium in lowering the ductile-brittle transition temperature of group VIA metals (ref. 9).

Tensile tests were conducted on Mo-Re alloys to permit a direct comparison between hardness and yield stress to determine the validity of using hardness as a measure of flow stress for the alloys studied.

Re contents ranged from zero up to the maximum solubility of Re in each of the group VIA metals. Test temperatures ranged from 0.02 to 0.2 T_m of the unalloyed metal. A microhardness testing unit was modified to permit testing over the desired temperature range. Hardness was measured for approximately 14 alloys from each system at six test temperatures.

SYMBOLS

c	rhenium content
E	bulk modulus
H	hardness
H^H	alloy hardening
$H^{H'}, H_o^H$	alloy hardening extrapolated to $c = 0$ and $T = 0$, respectively
H^S	alloy softening
$H^{S'}, H_o^S$	alloy softening extrapolated to $c = 0$ and $T = 0$, respectively
m, n, p, s	constants
T	temperature
T_m	melting temperature
T_s	discontinuity temperature
σ	yield stress

EXPERIMENTAL PROCEDURE

Materials

The unalloyed metals and alloys studied in this program are presented in table I. Unalloyed chromium and molybdenum and the chromium-rhenium (Cr-Re) and molybdenum-rhenium (Mo-Re) alloys were prepared by nonconsumably arc melting 70-gram charges followed by drop casting into a water-cooled copper mold. Iodide chromium and electron-beam-melted rhenium were used for Cr-Re alloys. High purity Mo and Re powders were used for Mo-Re alloys. Tungsten alloys were perpared by electron-beam melting pressed and sintered electrodes of high purity powders of tungsten and rhenium. Ingots were fabricated to rods by extruding and swaging. Analyzed rhenium contents and typical interstitial contents are listed in table I.

Cubic specimens approximately 7 millimeters on a side were cut from Cr-Re and Mo-Re cast ingots. Specimens approximately 8 millimeters in diameter by 4 millimeter high were cut from tungsten-rhenium (W-Re) swaged rod. Specimens were annealed at 0.7 T_m of the parent metal in order to produce equiaxed, strain-free specimens. As a final preparation specimens were given a metallographic polish on the face to be used for hardness impressions.

TABLE I. - CHEMICAL ANALYSES OF

GROUP VIA RHENIUM ALLOYS

(a) Rhenium content

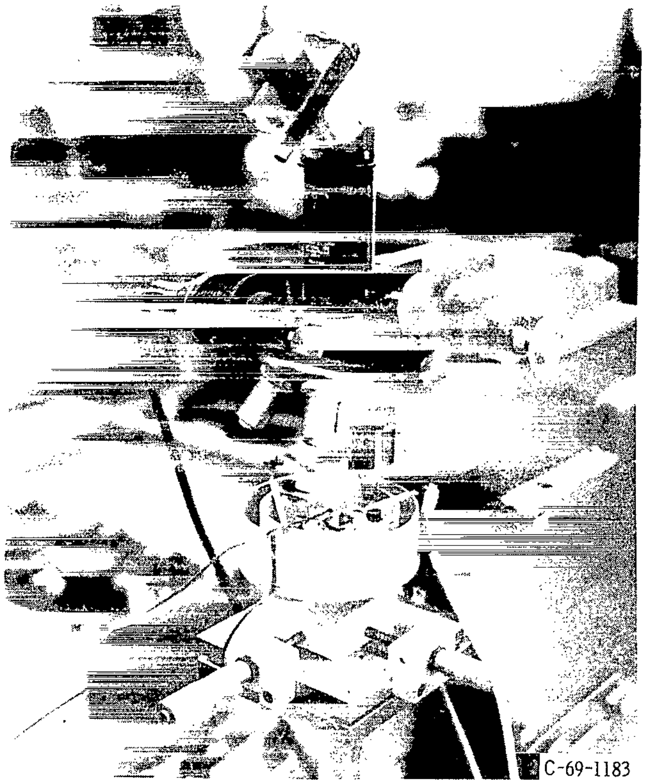
Rhenium content, at.% in -					
Cr-Re		Mo-Re		W-Re	
Nominal	Analyzed	Nominal	Analyzed	Nominal	Analyzed
0	0	0	0	0	0
.5	.5	.5	.6	1	1.0
1	1.0	2	2.0	2	1.9
2	2.0	3	3.0	3	2.8
3	3.0	4	4.2	4	3.3
5	4.7	5	5.1	5	5.0
7	6.8	6	5.9	8	7.7
9	9.3	7	7.1	9	9.0
12	12.6	8	8.0	12	11.6
15	15.8	10	9.7	15	15.4
20	22.0	15	13.9	20	20.2
30	29.2	20	19.5	22	22.0
35	34.1	25	23.7	24	23.2
40	37.7	30	32.1	26	25.3
		36	38.1	28	28.7
				30	30.4
				34	33.5

(b) Typical interstitial contents

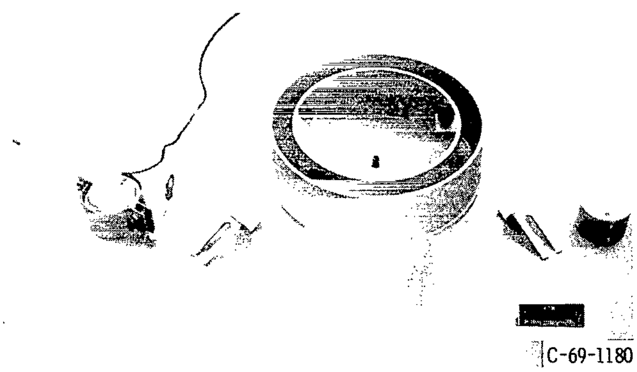
Impurity	Cr-Re alloy		Mo-Re alloy		W-Re alloy	
	ppm	at.%	ppm	at.%	ppm	at.%
Carbon	101	0.0437	59	0.0471	3	0.0046
Hydrogen	3.1	.0160	.8	.0076	--	------
Nitrogen	46	.0171	4	.0027	<5	<.0066
Oxygen	58	.0188	18	.0108	2	.0023

APPARATUS

A microhardness testing unit was modified to permit hardness determinations over the temperature range 77 to 730 K. Figure 1(a) shows the modified hardness unit equipped to determine hardness above room temperature. This was accomplished by wrapping a resistance heated Nichrome coil around a copper specimen support block. Temperature was measured by means of a thermocouple attached to the copper block,



(a) Assembled test unit.



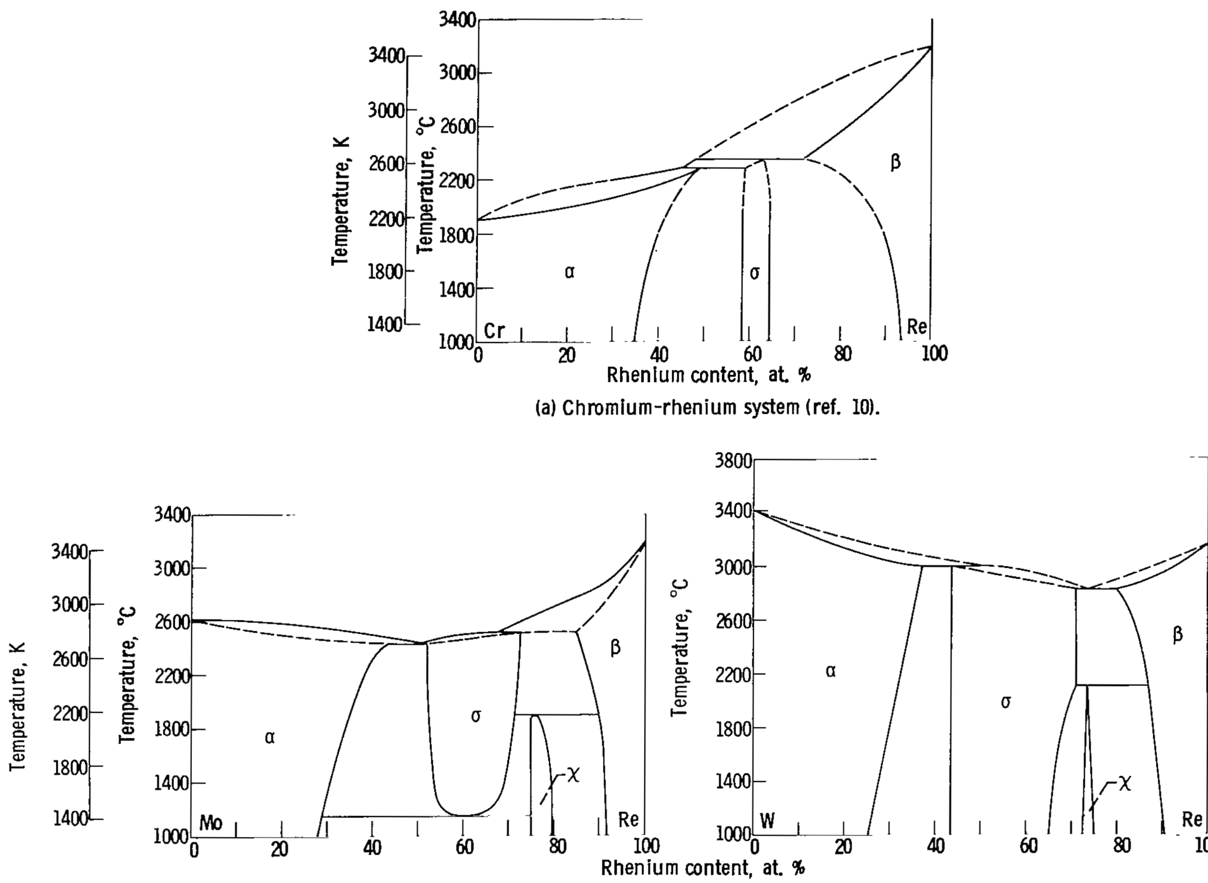
(b) Heating and cooling stages.

Figure 1. - Modified microhardness test unit.

shown in more detail in figure 1(b). Temperature was controlled automatically by means of a proportional controller. For temperatures below room temperature, liquid nitrogen was poured into the outer chamber of the hardness testing apparatus shown in figure 1(b). The inner chamber was then filled with alcohol or liquid nitrogen which served as the cooling medium to lower the specimen temperature to the desired level. Temperature was controlled by the rate of liquid nitrogen addition and could be held within ±1 K during a test.

Procedure

A minimum of 10 diamond pyramid hardness impressions were made on each alloy at each test temperature. A load of 1 kilogram and a dwell time of 15 seconds were used for the impressions. Hardness readings were taken only of impressions within the



(a) Chromium-rhenium system (ref. 10).

(b) Molybdenum-rhenium system (refs. 11 to 13).

(c) Tungsten-rhenium system (refs. 14 and 15).

Figure 2. - Phase diagrams of group VIA rhenium alloy systems.

grains. Test temperature was selected based on fraction of the melting point of the parent metal and nominally covered the range from 0.02 to 0.2 T_m. Rhenium contents ranged from zero up to approximately the maximum high-temperature solubility of rhenium in the group VIA metals (refs. 10 to 15) which as noted in figure 2 corresponds to 45 atomic percent in chromium, 40 atomic percent in molybdenum, and 35 atomic percent in tungsten.

RESULTS

Composition Dependence of Hardness

Hardness data are summarized in table II for the three alloy systems investigated. Figure 3 shows the effect of rhenium content on hardness in the group VIA metals. Alloy softening, characterized by a decrease in hardness with increase in rhenium content, is observed to be similar for the three alloy systems. Alloy softening is observed at homologous temperatures less than 0.14 in Cr-Re and Mo-Re alloys and less than 0.16 for W-Re alloys. Also of interest in figure 3 is the relatively low hardness of the alloys at 77 K compared to the unalloyed metals. Hardnesses of even the more concentrated alloys were less than those of the unalloyed group VIA metals.

It should also be noted in figure 3 that the rhenium content required to produce a hardness minimum diminishes rapidly as test temperature is increased. Figure 4 illustrates the dependence of rhenium content at the hardness minimum on temperature expressed as a fraction of the melting point. The similarity of the hardness minima locations in all three systems is a further indication that the group VIA metals are similar in alloy softening behavior when alloyed with rhenium.

Temperature Dependence of Hardness

The temperature dependence of hardness for group VIA rhenium alloys is illustrated in figure 5. A similar response to temperature is noted for the three alloy systems. At rhenium concentrations less than about 16 atom percent, hardenss is observed to increase rapidly as test temperature decreases. In contrast, alloys in all three systems with rhenium contents from 16 atom percent to the maximum solubility of rhenium in group VIA metals exhibited a smaller increase in hardness as test temperature decreased.

TABLE II. - SUMMARY OF HARDNESS DATA FOR

GROUP VIA RHENIUM ALLOYS

(a) Alloy system, chromium-rhenium

Rhenium content, at. %	Temperature ratio, T/T_m					
	0.038	0.081	0.119	0.138	0.163	0.200
	Temperature, T, K					
	77	175	255	300	350	430
	Hardness, VHN					
0	448	277	166	127	96	86
.5	434	273	163	121	102	92
1.0	423	262	161	133	124	119
2.0	391	254	165	140	131	121
3.0	388	246	175	165	160	147
4.7	352	267	221	205	202	187
6.8	340	274	236	216	211	198
9.3	357	291	257	254	241	227
12.6	366	305	270	262	242	223
15.8	406	320	293	281	265	238
22.0	413	354	314	305	279	258
29.2	421	377	338	324	303	289
34.1	437	400	350	332	316	296
37.7	446	392	341	334	299	289

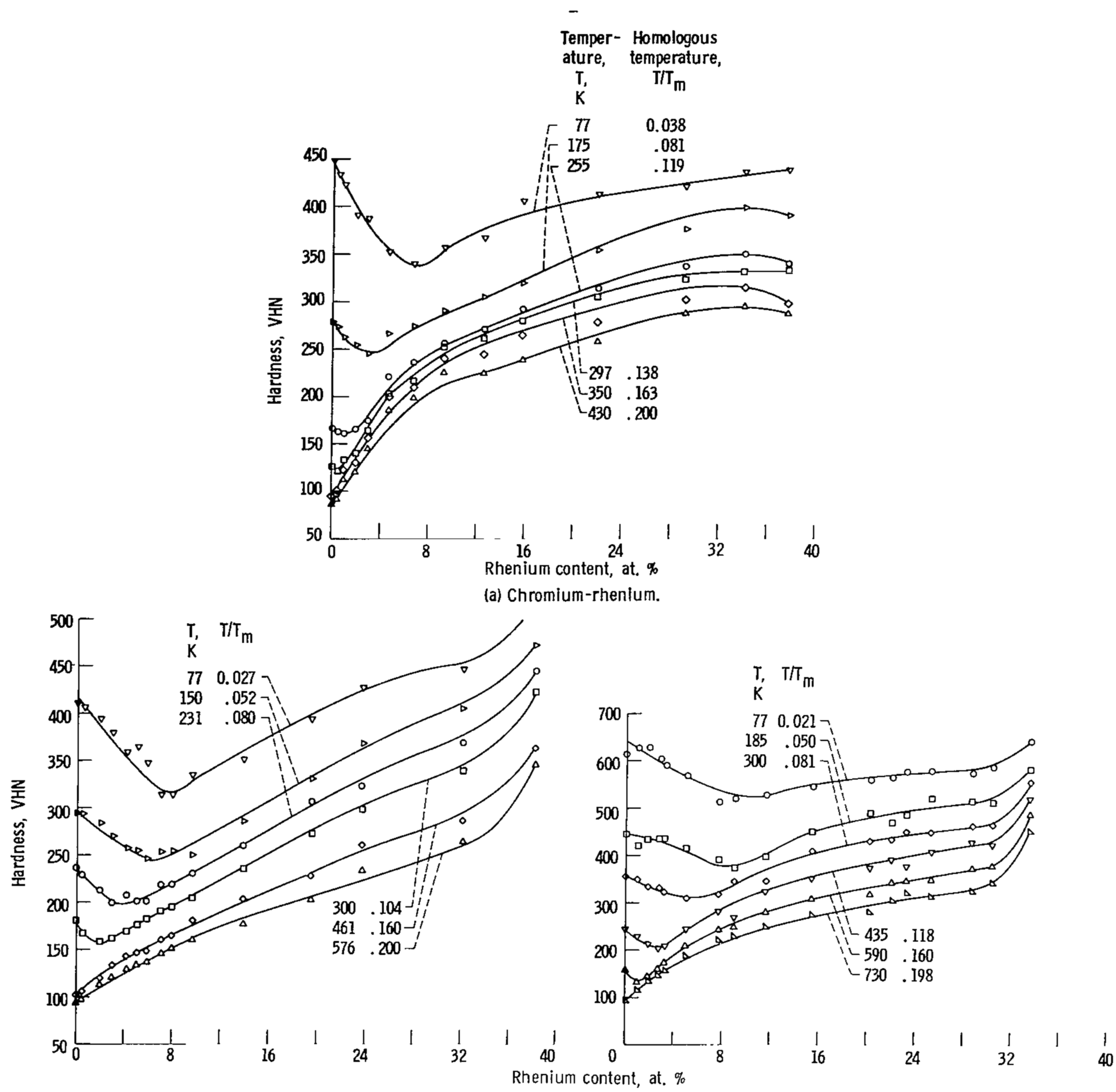
(b) Alloy system, molybdenum-rhenium

Rhenium content, at. %	Temperature ratio, T/T_m					
	0.027	0.052	0.080	0.104	0.160	0.200
	Temperature, T, K					
	77	150	231	300	461	576
	Hardness, VHN					
0	412	295	238	182	103	93
.6	406	294	230	167	106	97
2.0	395	283	213	157	119	113
3.0	380	270	200	163	134	122
4.2	358	257	208	168	144	129
5.1	365	256	202	176	147	134
5.9	348	247	202	183	148	136
7.1	326	253	219	192	161	145
8.0	327	254	220	196	165	152
9.7	335	251	230	205	182	162
13.9	351	287	260	237	203	178
19.5	394	331	308	273	228	202
23.7	428	368	324	299	262	234
32.1	447	406	368	339	287	265
38.1	534	472	446	424	365	347

TABLE II. - Concluded. SUMMARY OF HARDNESS DATA FOR GROUP VIA RHENIUM ALLOYS

(c) Alloy system, tungsten-rhenium

Rhenium content, at. %	Temperature ratio, T/T_m					
	0.021	0.050	0.081	0.118	0.160	0.198
	Temperature, T, K					
	77	185	300	435	590	730
	Hardness, VHN					
0	613	446	357	245	159	93
1.0	627	421	348	229	131	115
1.9	627	431	331	213	145	140
2.8	604	436	331	201	162	145
3.3	591	436	323	210	171	156
5.0	569	416	308	247	213	188
7.7	515	392	319	283	245	224
9.0	520	375	348	270	250	230
11.6	527	398	348	324	282	249
15.4	547	451	411	352	313	274
20.2	561	492	431	373	320	279
22.0	565	469	434	393	346	303
23.2	579	486	453	378	348	321
25.3	578	522	448	408	398	313
28.7	574	515	463	428	375	325
30.4	587	512	466	424	380	341
33.5	643	583	557	522	489	454



(a) Chromium-rhenium.

(b) Molybdenum-rhenium.

(c) Tungsten-rhenium.

Figure 3. - Hardness dependence of group VIA metals on rhenium content.

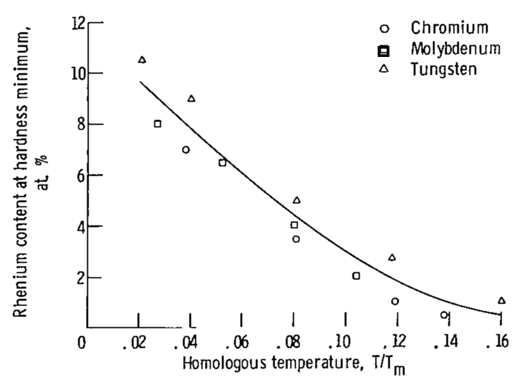


Figure 4. - Variation of rhenium content at hardness minimum with temperature.

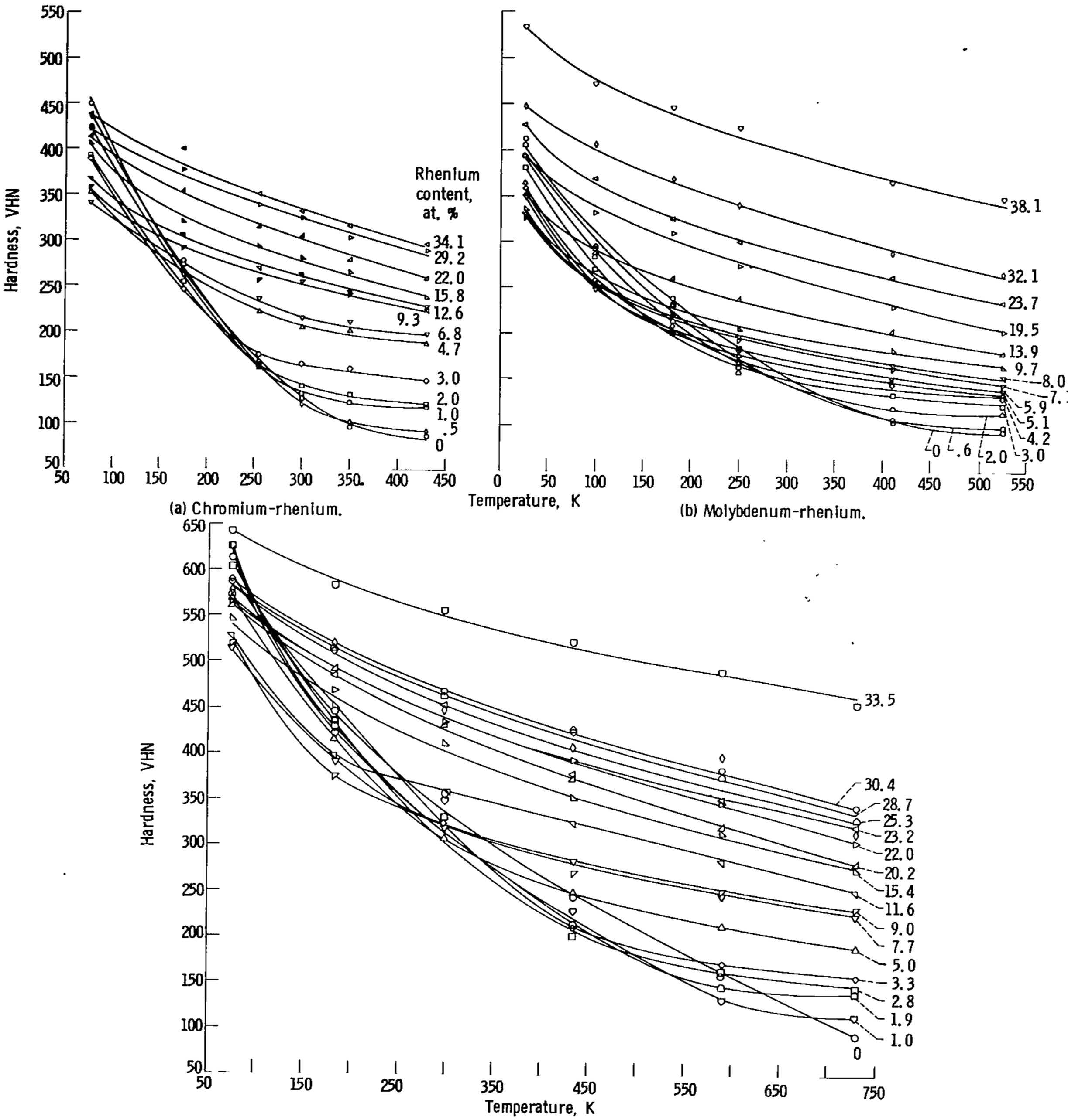


Figure 5. - Hardness dependence of Group VIA-Re alloys on temperature.

Correlation Between Hardness and Yield Stress

A comparison was made of hardness and yield stress for several Mo-Re alloys to determine if hardness is proportional to the flow strength of the alloys investigated. Specimens of molybdenum alloyed with 0, 2, 6, and 8 atom percent rhenium were tested in tension over the temperature range used for hardness tests. The hardness and yield

TABLE III. - YIELD STRESS DATA FOR Mo-Re ALLOYS

Rhenium content, at.%		Temperature, K	Yield stress, σ		Yield-stress ratio,
Nominal	Analyzed		ksi	MN/m^2	$\sigma_T/\sigma_{T\ 300\ K}$
0	0	300	38.4	265	1.0
		338	32.2	222	.84
		500	15.6	108	.41
2	1.7	150	83.3	574	2.14
		231	56.0	386	1.44
		300	39.0	269	1.00
		461	26.5	183	.68
		576	24.0	165	.62
6	5.9	231	50.8	350	1.34
		300	38.0	262	1.00
		461	26.4	182	.69
		576	23.4	161	.62
8	7.7	77	115.0	793	2.50
		150	76.1	525	1.65
		231	53.4	368	1.16
		300	46.0	317	1.00
		461	32.3	222	.70
		578	28.4	196	.62

stress data (table III) are compared in figure 6(a) as ratios to the hardness or yield stress at room temperature (300 K). The curves are drawn to average both sets of data. There is good agreement between the temperature dependence of hardness and yield stress for Mo-Re alloys.

Raffo (ref. 16) has determined the temperature dependence of yield stress for unalloyed tungsten and tungsten alloyed with 1, 2, 7, and 25 atom percent rhenium and the data are plotted in figure 6(b) where a similar comparison of hardness and yield stress is made for W-Re alloys. The data again illustrate good agreement of the temperature

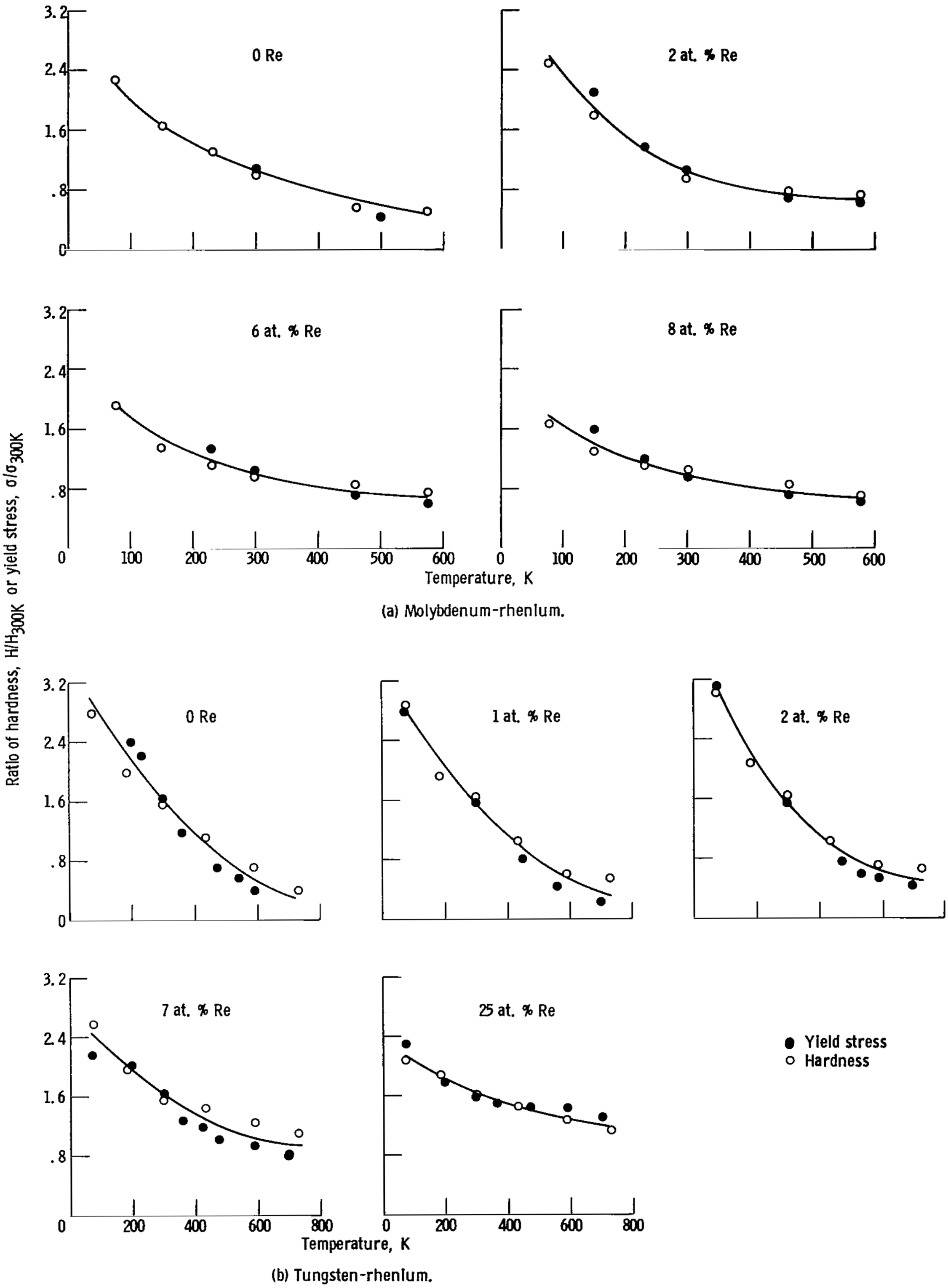


Figure 6. - Comparison of hardness and yield stress for molybdenum-rhenium and tungsten-rhenium alloys.

dependency of hardness and yield stress. Tensile data were not available for Cr-Re alloys and no comparison was made for this system.

The practical significance of the correlation between hardness and yield stress is that simple hardness test may be used to characterize the temperature dependency of flow stress for group VIA metals and alloys and presumably other bcc metals at low temperatures.

DISCUSSION

In the preceding section alloy softening was observed in group VIA metals alloyed with rhenium as characterized by a decrease in hardness with increase in rhenium content at homologous temperatures less than 0.16 and for rhenium contents less than 16 atom percent. The purpose of this section is to analyze the hardness data in terms of alloy softening and hardening and to correlate hardness with temperature and rhenium concentration. The hardness data presented in figure 3 suggest that the rate of alloy hardening may be separated from other factors influencing hardness by considering the hardness as a function of rhenium content curves in figure 3 at temperatures greater than 0,16 T_m. Hardening only is observed at these temperatures, and it is assumed that hardness is fully controlled by alloy hardening with no contribution from alloy softening. It is further assumed that, at temperature less than 0.16 T_m, alloy hardening controls the hardness behavior of the alloys having rhenium contents in excess of the rhenium concentrations at the hardness minima since the hardening rates appear to parallel the hardening rates at temperatures greater than 0.16 T_m. A schematic representation of the hardness behavior of the alloys at $T_m < 0.16\ T_m$ is shown in figure 7. Alloy hardening H^H is noted to increase monotonically with rhenium content while alloy softening H^S decreases monotonically with rhenium content. The measured hardness

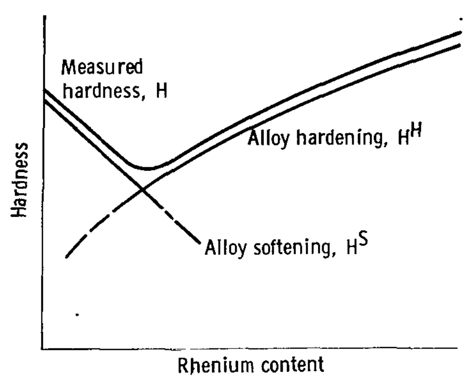


Figure 7. - Schematic representation of hardness for group VIA rhenium alloys.

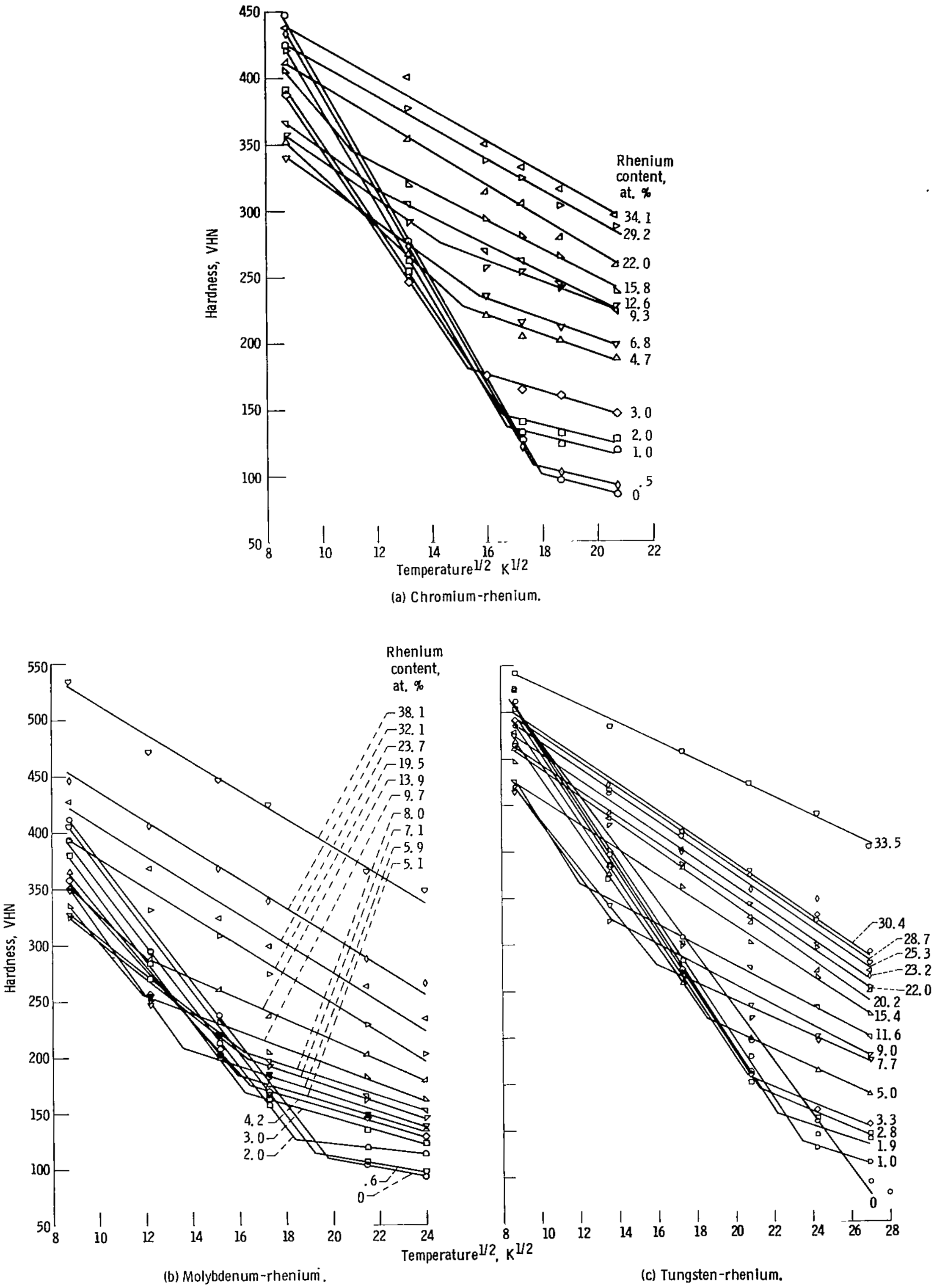


Figure 8. - Linear relation between hardness and $T^{1/2}$.

H curve is the higher of the alloy softening or alloy hardening curves. Thus, it appears that hardness behavior of group VIA rhenium alloys at temperatures less than $0.16\ T_m$ is controlled by two separate and distinct effects.

Correlation of Hardness with Temperature and Rhenium Content

The temperature dependence of hardness was illustrated in figure 5 for the three alloy systems investigated. The primary point of interest is the reduction in the temperature dependence of hardness as rhenium is added to group VIA metals. At low temperatures and low rhenium contents there is a sharp increase in hardness as temperature decreases. At higher tempratures, for the group VIA metals alloyed with up to approximately 16 atom percent rhenium, the temperature dependence is much lower and comparable to the more concentrated alloys over the entire temperature range.

The change in hardening rate with decreasing temperature is illustrated more clearly in figure 8 where hardness is plotted against $T^{1/2}$. It is observed that plots of H against $T^{1/2}$ for the dilute alloys can be separated into two linear portions. The discontinuity occurs at lower temperatures as rhenium content increases until at approximately Cr-22Re, Mo-13.9Re, and W-15.4Re, a liner relation exists between H and $T^{1/2}$ over the entire temperature range. The temperature where the discontinuity occurs for dilute alloys will be disignated T_s. At temperatures less than T_s hardness is very temperature sensitive while at temperatures greater than T_s hardness is much less sensitive to temperature. As will be discussed later, alloy softening occurs at temperature less than T_s while alloy hardening occurs at temperatures greater than T_s.

Hardness data, divided by bulk modulus E (see table), at temperatures less than T_s in figure 8 are plotted against rhenium content c as shown in figure 9(a). The

	Bulk modulus, E	
	kg/mm^2	MN/m^2
Chromium	29.0	285 000
Molybdenum	32.3	317 000
Tungsten	40.8	400 000

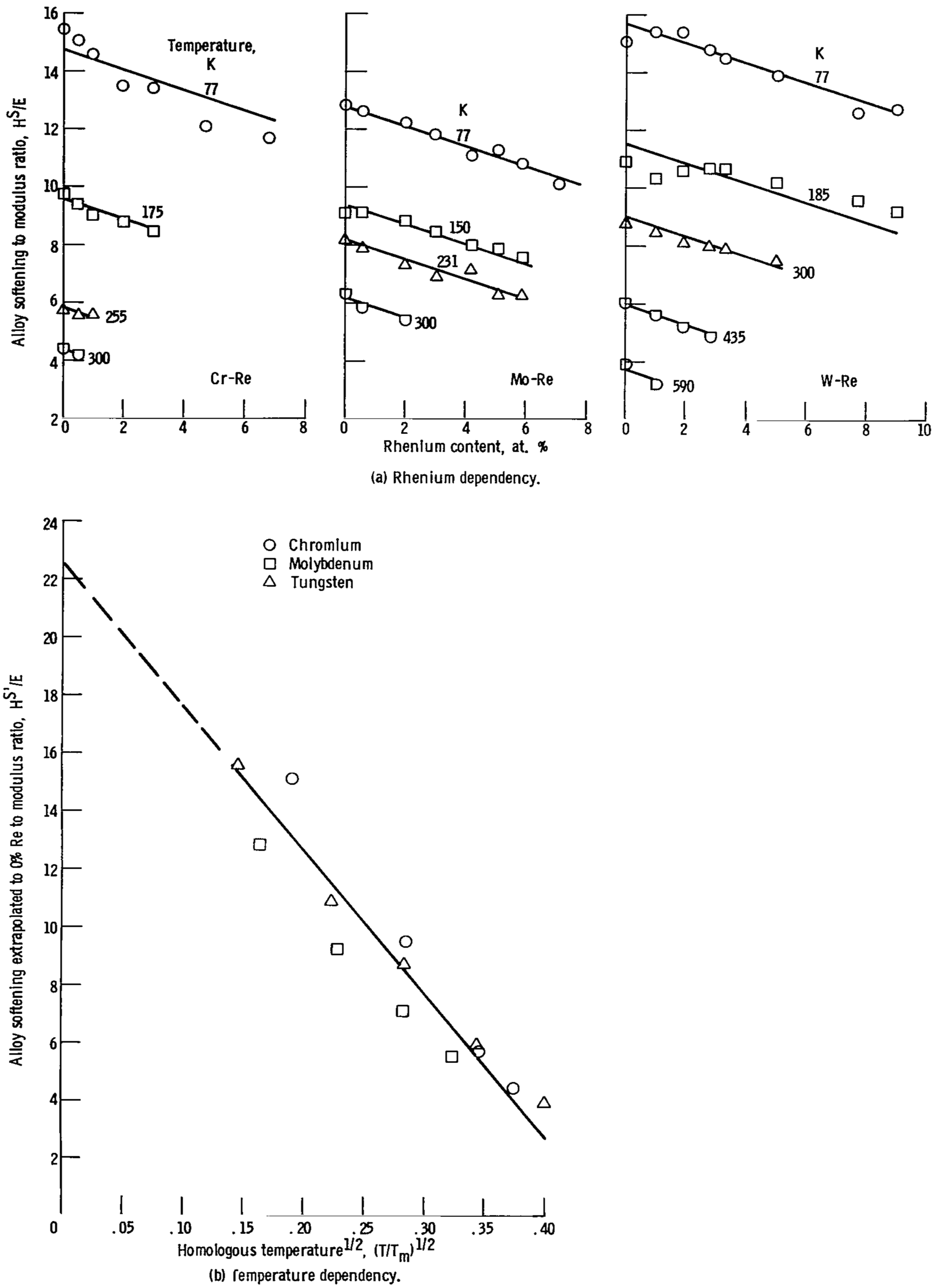


Figure 9. - Rhenium and temperature dependency of alloy softening in group VIA metals.

hardness H^S in this region is a result of alloy softening. It should be noted that H varys linearly with c for the three alloy systems. Slopes obtained from least squares fit of the data at each temperature were averaged and lines having a common slope were drawn through the data in figure 9(a). Alloys softening data obey a relation of the form

$$\frac{H^S}{E} = \frac{H^{S'}}{E} + nc \tag{1}$$

where $H^{S'}$ is the hardness at zero rhenium content in the temperature range where alloy softening is observed and the slope n is a constant. In figure 9(b) the intercepts from figure 9(a) ($H^{S'}/E$) are plotted against square root of homologous temperature. Chromium and tungsten alloy data are noted to fit a least squares line reasonably well while the Mo alloy data lie slightly below the line representing an average of the data. A complete relation between H, c, and T can now be written for alloy softening of the form

$$\frac{H^S}{E} = \frac{H_o^S}{E} + nc + p\left(\frac{T}{T_m}\right)^{1/2} \tag{2}$$

where H_o^S is the extrapolated hardness at 0 K for the unalloyed metals in the alloy softening region and the slope p is a constant. The values of H_o^S, n and p are 22.6, -0.34, and -50, respectively.

Alloy hardening data represented by the resultant hardnesses H^H at temperatures greater than T_S in figure 8 can also be correlated with rhenium content and temperature. In figure 10(a) hardness divided by modulus H^H/E is plotted against square root of rhenium content. The slopes were determined by a least squares fit of the data and averaged. Lines having a common slope were then drawn through the data. At low temperatures and at high rhenium contents agreement is good. At high temperatures and low rhenium contents, especially for the Mo-Re alloys, considerable departure from the straight line exi sts. This suggest that alloy softening may still be affecting the hardness in this region. The alloy hardening data fit a relation of the form

$$\frac{H^H}{E} = \frac{H^{H'}}{E} + mc^{1/2} \tag{3}$$

where $H^{H'}$ is the hardness extrapolated to zero rhenium content in figure 10(a) and the slope m is a constant. The extrapolated harnesses $H^{H'}/E$ are plotted against square root of homologous temperature in figure 10(b), and they approximate a straight line

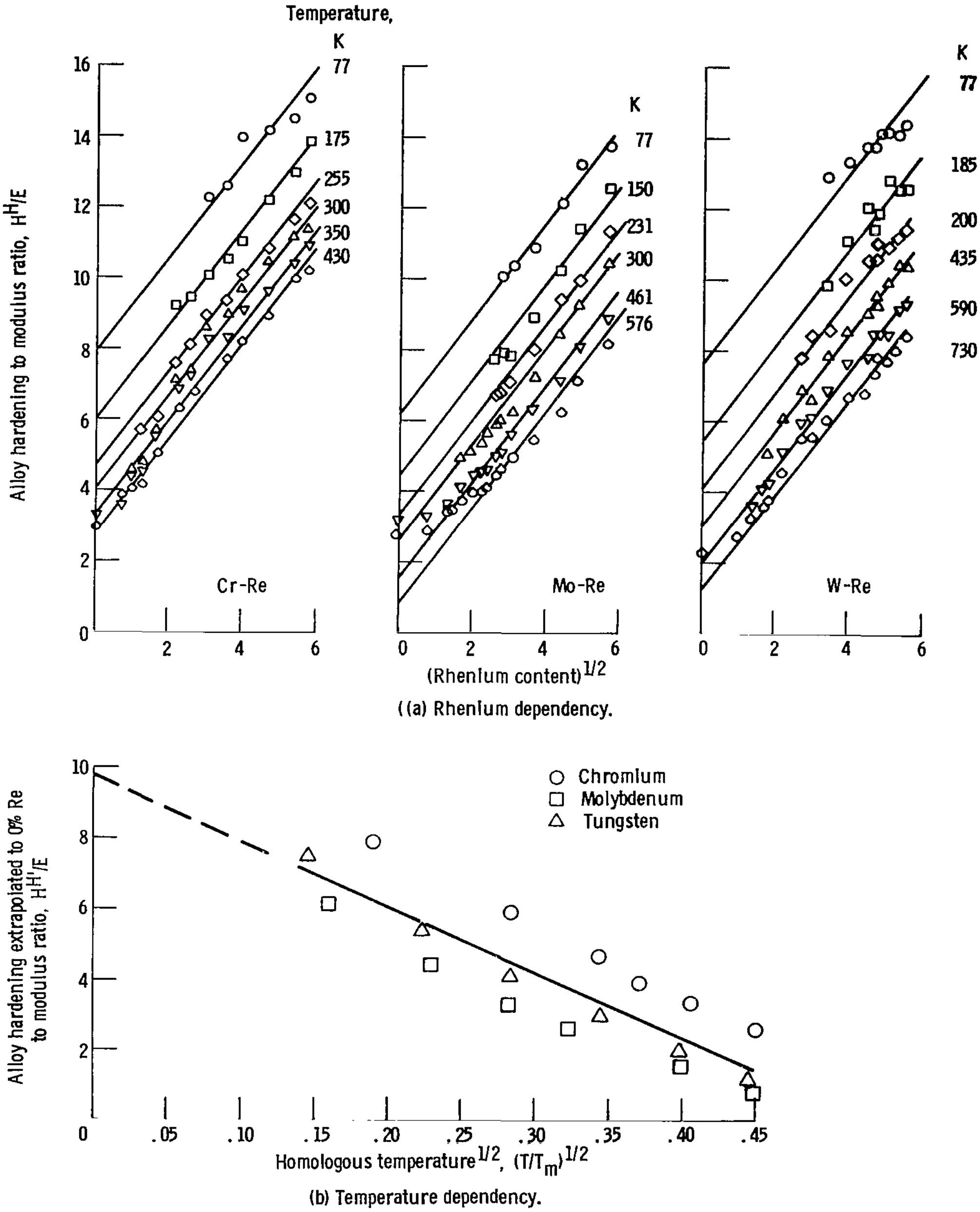


Figure 10. - Rhenium and temperature dependency of alloy hardening in group VIA metals.

reasonably well. This leads to a complete relation between H, c, and T for alloy hardening of the form

$$\frac{H^H}{E} = \frac{H_o^H}{E} + mc^{1/2} + s\left(\frac{T}{T_m}\right)^{1/2} \tag{4}$$

where H_o^H is the extrapolated hardness at 0 K for the unalloyed metals in the alloy hardening region and the slope s is a constant. The values of H_o^H/E, m and s are 9.8, 1.4, and -18.4, respectively.

Alloy softening and alloy hardening can thus be related empirically to c and T by equations (2) and (4). It is postulated that equations of this type can be used to predict whether alloy softening or alloy hardening can be expected at a selected alloy composition and temperature for other group VIA alloys. By sustituting for T and c in equations (2) and (4) the higher hardness indicates which equation is valid for the selected conditions and therefore whether softening or hardening occurs. The equations should make it possible to fully characterize the hardness behavior of an alloy system by preselecting only a few critical compositions and temperatures to investigate, thus reducing the amount of experimental work required.

Mechanisms of Alloy Softening in Group VIA Metals

The current results show that alloy softening in group VIA rhenium alloys characterized by a substantial reduction in hardness is accompanied by a sharp temperature dependence of hardness. Alloy hardening in contrast is accompained by only a lesser temperature dependence of hardness. A reduction in yield stress can also be obtained in group VIA metals by purification as a result of electron-beam zone melting. Lawley, Van den Syke, and Maddin (ref. 18) and Koo (ref. 19) have shown that for molybdenum and tungsten, respectively, increasing from 1 to 5 or 6 zone melting passes substantially reduces the yield stress. More recently Stein (ref. 20) has shown that zone-melting molybdenum followed by zirconium hydride purification leads to a decrease in temperature dependence of yield stress with increasing purity where carbon was postulated to be the hardening element that was removed. These results coupled with results of Smialek Webb, and Mitchell (ref. 21) and Ravi and Gibala (ref. 8) in group VA metals cannot be explained by a theory based on a Peierls force since it is assumed that the thermal component of stress is independent of purity or structure. The preceding authors have attributed alloy softening in group VA alloys to scavenging of interstitial impurities by solute additions.

Evidence for similar scavenging of impurities in group VIA metals is afforded by field ion microscopy study by Novick and Machlin (ref. 22) of W-Re alloys where results were interpreted to indicate that rhenium in solid solutions at concentrations of 1.25 or 3.0 atom percent scavenged oxygen from dislocation and grain boundary sites. Rhenium was postulated to act as an electron donor and to combine with oxygen to form local clusters of rhenium-oxygen complexes. Interpretation of field ion microscope micrographs has been questioned by Soffa and Moazed (ref. 23) so that it can not be stated unequivacally that rhenium scavenges oxygen or other interstitial impurities in group VIA metals. There is also no direct evidence available that such scavenging produces alloy softening.

An alternate explanation for alloy softening is that rhenium additions lower the relatively high Peierls stress in bcc group VIA metals. It has been postulated by Arsenault (ref. 24) that rhenium additions can affect the electronic structure of the solute element, which in turn determines the magnitude of the Peierls stress. The unfilled d shells in most bcc metals leads to nonspherical orbits which produce directional forces between atoms and thus to a high Peirels stress. If a solute atom such as rhenium acts as an electron donor, filling the d shells, then the orbits become more spherical, leading to a reduction in the bond directionality and thus a reduction in the Peierls stress. It was further reasoned that the bcc alkali metals which have only s electrons, would have a small Peierls stress based on electron structure and thus exhibit a small temperature dependence of yield stress. An investigation of potassium by Hull and Rossenburg (ref. 25) did show a small temperature dependence of yield stress.

The present results can not differentiate between the two preceding mechanisms. However, lowering the Peierls stress is favored based on the solubility of interstitials in group VIA metals. Table IV lists the maximum solubility of interstitial elements carbon, nitrogen, and oxygen in group VIA metals (refs. 26 to 28). It should be noted that the total solubility of interstitial impurities in chromium is an order of magni-

TABLE IV. - MAXIMUM SOLUBILITIES OF C, N, AND O IN GROUP VIA METALS

Group VIA metal	Maximum solubility,[a] At.%			Total solubility, at.%
	Carbon	Nitrogen	Oxygen	
Chromium	1.4	0.96	0.1	2.46
Molybdenum	.176	.023	.018	.217
Tungsten	.3	.005	.06	.365

[a]Refs. 26 to 28.

tude greater than in molybdenum or tungsten. In addition, chromium cannot be purified by electron beam melting in high vacuum because of its high vapor pressure. Therefore, interstitial impurities are normally at a much higher level in arc melted chromium than in electron beam melted molybdenum or tungsten. It would be expected that if scavenging of interstitials by rhenium were the operating mechanism much more rhenium would be required to be as effective in chromium as in molybdenum or tungsten because of the greater concentration of interstitials in chromium. However, it was observed in figures 4 and 9(b) that alloy softening upon adding rhenium to group VIA metals is quite similar pointing to an inherent property such as electron structure which in turns determines the magnitude of the Peierls stress.

The similarities in phase diagrams shown in figure 2 can be attributed to the electron structure of the transition metals (ref. 29). Alloys with equivalent electron structures may be expected to exhibit similar mechanical properties. Stephens and Klopp (ref. 30) have indeed shown that alloy hardening in chromium containing additions of rhenium, ruthenium, iron, cobalt, iridium, osmium, or manganese up to 50 atom percent solute can be correlated with the number of valency electrons per atom contributed by the solute atoms. It may thus be possible that initial alloy softening may be associated with electron structure of bcc transition metal alloys as well.

CONCLUSIONS

A study of low-temperature hardness behavior of group VIA metals alloyed with rhenium in quantities ranging from zero to maximum solubility in chromium, molybdenum, and tungsten has yielded the following conclusions:

1. Alloy softening is similar in all three systems, occurring at temperature less than 0.16 T_m and at rhenium concentrations less than about 16 atom percent.

2. The rhenium content required to produce a hardness minimum diminishes rapidly at a common rate for all three alloy systems as test temperature is increased.

3. Hardness is highly temperature sensitive for alloys exhibiting alloy softening and less temperature sensitive for alloys exhibiting alloy hardening.

4. Alloy hardening is similar in all three alloy systems occurring, over the entire temperature range investigated for alloys containing greater than 16 atom percent rhenium.

5. In group VIA-rhenium alloys, alloy softening is believed to be controlled by electron structure.

Lewis Research Center,
National Aeronautics and Space Administration,
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