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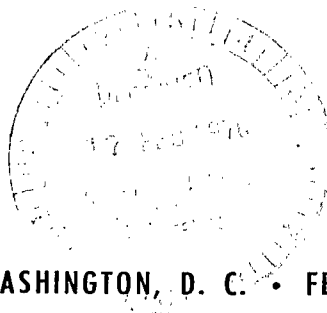
ALLOY SOFTENING IN BINARY IRON SOLID SOLUTIONS

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16. Abstract

An investigation was conducted to determine softening and hardening behavior in 19 binary iron-alloy systems. Microhardness tests were conducted at four temperatures in the range 77 to 411 K. Alloy softening was exhibited by 17 of the 19 alloy systems. Alloy softening observed in 15 of the alloy systems was attributed to an intrinsic mechanism, believed to be lowering of the Peierls (lattice friction) stress. Softening and hardening rates could be correlated with the atomic radius ratio of solute to iron. Softening observed in two other systems was attributed to an extrinsic mechanism, believed to be associated with scavenging of interstitial impurities.

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SUMMARY

An investigation was conducted to characterize the softening and hardening behavior of binary iron (Fe) alloys at temperatures in the range 77 to 411 K. These temperatures correspond to a homologous temperature range of 0.043 to 0.227 T_m (where T_m is the melting temperature of Fe) and coincide with the temperature range where alloy softening is generally observed in body-centered-cubic metals. A total of 19 binary Fe-alloy systems were investigated. Alloys were prepared by arc-melting of high-purity Fe and high-purity solute additions. The primary means of evaluation was hardness testing, which is an expedient means of determining the mechanical behavior of such a large number of alloys.

Results showed that the atomic radius ratio of solute to Fe was the primary factor in controlling low-temperature hardness of the binary Fe alloys. Alloy softening observed in 15 of the alloy systems was attributed to an intrinsic mechanism, believed to be lowering of the Peierls (lattice friction) stress. The 15 alloy systems that exhibited alloy softening similar to softening observed in other body-centered-cubic systems included those with titanium, vanadium, chromium, molybdenum, tungsten, manganese, rhenium, ruthenium, osmium, cobalt, rhodium, iridium, nickel, palladium, and platinum. Both softening and hardening rates could be correlated with solute-to-Fe atomic radius ratios. The atomic radius ratios of the 15 solutes all lie within the ±15 percent size limit considered favorable for solid-solution formation in Fe. The remaining four solute additions lie outside this favorable-size zone. Alloy softening was observed at very low solute concentrations with niobium and tantalum additions and is attributed to an extrinsic mechanism, probably associated with scavenging of interstitial impurities. Alloy softening did not occur in binary Fe-zirconium and -hafnium alloy systems, probably because of the very large solute-to-iron atomic radius ratios for these systems.

INTRODUCTION

Alloy softening in body-centered-cubic (bcc) metals is a well-established phenomenon. The extent of current interest in alloy softening in iron (Fe) as well as other bcc metals is evident from the bibliographies in the review papers by Leslie (ref. 1) and Pink (ref. 2) as well as in the more recent paper by Leemans and Fine (ref. 3). These papers conclude that alloy softening occurs at low temperatures in bcc metals as a result of either substitutional or interstitial alloy additions. As noted by Pink (ref. 2), the amount of interstitial solute required to produce maximum softening at low temperatures normally ranges from 0.02 to 0.05 at.%. This is much lower than the 2 to 10 at.% concentration of substitutional solutes that is usually required to produce softening under similar test conditions. These results suggest that there may be more than one mechanism controlling alloy softening for the two types of solute additions.

Our previous results for other bcc metals (refs. 4 to 7) also suggest that more than one mechanism may be operative in alloy softening, dependent upon the solvent metal. Alloy softening in Group VI solvent metals, chromium (Cr), molybdenum (Mo), and tungsten (W), could be correlated with the electron concentration in the alloys (refs. 4 to 6). In contrast, we attributed alloy softening in a Group V solvent metal, niobium (Nb), to scavenging of interstitial impurities (ref. 7). This is in agreement with the previously reported findings of others on softening in Nb and tantalum (Ta) (refs. 8 and 9). Alloy softening in Fe has been attributed to an extrinsic mechanism (i.e., scavenging of interstitial impurities), as well as to intrinsic mechanisms, such as lowering of the Peierls stress (ref. 10).

Many of the previous studies on softening in Fe alloys have involved only two or three alloy systems and have covered only a small concentration range (refs. 3 and 10 to 13). In order to reduce the effects of interstitial impurities in Fe, several investigators have added titanium (Ti) to Fe to "getter" carbon (C), oxygen (O), and nitrogen (N) (refs. 1 and 10). Because of the limited scope of these studies, the variation in purity of the iron alloys, and the possible complicating effects due to "gettering" of Fe by Ti, it is not possible to compare the results of the different investigations. The most comprehensive study on Fe alloys to date was the work of Leslie (ref. 1).

The purposes of our investigation were twofold. The primary purpose was to determine if alloy softening in Fe alloys was dependent upon electron concentration in a manner similar to that observed in Group VI metals or upon scavenging of interstitial impurities as observed in Group V metals. A secondary purpose was to provide a direct comparison of alloy softening and hardening in several binary Fe-alloy systems having the same processing history.

Alloy additions to Fe included the elements in the portion of the Periodic Table

shown in figure 1 (with the exception of technetium). A total of 19 alloy systems were investigated. Hardness testing was used as the primary means of evaluation since it provides an expedient method of determining the mechanical properties of a large number of alloys. Testing was conducted at four temperatures over a homologous temperature range of 0.043 to 0.227 T_m (where T_m is the absolute melting temperature of unalloyed Fe) in order to encompass the temperature range where alloy softening is generally observed in bcc alloys.

EXPERIMENTAL PROCEDURE

Materials

Table I presents the analyzed compositions of the Fe-base alloys in atomic percent. Interstitial contents in ppm by weight are also listed in table I for several alloys from each alloy system. Starting materials for this investigation included vacuum-processed Fe and Ti; high-purity electron-beam-melted vanadium (V), Nb, Ta, Mo, W, and rhenium (Re); iodide Cr; electrolytic manganese (Mn), nickel (Ni), and cobalt (Co); commercial-purity zirconium (Zr) sheet, hafnium (Hf) turnings, and palladium (Pd) and platinum (Pt) foils; and hydrogen-annealed ruthenium (Ru), osmium (Os), rhodium (Rh), and iridium (Ir) powders.

Ingots were prepared by nonconsumable triple arc-melting of 70-gram charges in a water-cooled copper mold, followed by drop casting into a square-cross-section mold. Slices approximately 3 millimeters thick and 15 millimeters on a side were cut from the cast ingots for hardness testing. One face of each specimen that was to be used for hardness testing was given a metallographic polish. Specimens were normally annealed in a vacuum of 1×10^{-4} N/m^2 or better for 1 hour at the temperature where maximum solubility occurs in the α region. This anneal was followed by a 16-hour anneal at 300° C in order to produce single-phase, homogenized, equiaxed, strain-free specimens.

Procedure

Alloying elements for binary Fe alloys were selected from the fourth, fifth, and sixth periods of the Periodic Table and included all the solute elements in Groups IV to VIII with the exception of technetium, as shown in figure 1. Also shown in figure 1 are the number of bonding electrons (ref. 14) of the elements and the atomic radius ratio of solute element to Fe (ref. 15). The selection of solute concentration in each

alloy series was based on the Fe-solute phase diagrams (refs. 16 to 18). Solute concentrations ranged from approximately 0.5 at.% for those elements that have extremely limited solubility in Fe to approximately 16 at.% for those elements that form a continuous series of solid solutions with Fe.

Test temperatures were selected to cover the range where alloy softening is normally observed in Fe alloys, less than $0.11\ T_m$ (refs. 1 and 10), and also were extended to higher temperatures, where alloy hardening is usually observed. Test temperatures included 77, 188, 300, and 411 K or 0.043, 0.104, 0.166, and $0.227\ T_m$, respectively.

The modified microhardness test unit used in this study has been described previously (ref. 4). 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 grains. The relative standard deviation was 5 percent.

RESULTS

Solute Effects

Description of the effects of solute additions to Fe is arranged by Groups of the Periodic Table to facilitate presentation of the data. Figure 2 shows the hardness behavior of Fe alloyed with the Group IV elements Ti, Zr, and Hf. Alloy softening was observed at 77 K for Ti additions to about 4 at.%. The maximum solubility of Ti in Fe is nearly 8 at.% (ref. 16). For the Fe-8.12Ti alloy listed in table I, the hardness was 366 Vickers hardness number (VHN) at 77 K compared to 207 VHN for an Fe-3.86-Ti alloy at the same test temperature. This increase in hardness suggests that the solubility limit was exceeded at the higher Ti concentration. At 188 K, the hardness reached a minimum near 1.02 at.% Ti and then increased sharply at higher Ti contents. Alloy softening was not observed at 300 and 411 K in the binary Fe-Ti alloys. Figure 2 also shows the hardness response of binary Fe-Zr and Fe-Hf alloys. Both of these elements have extremely limited solubilities in Fe. Alloy softening was not observed in either of these two alloy systems at the four test temperatures used for this investigation.

The effects of the Group V elements V, Nb, and Ta on the hardness of Fe are shown in figure 3. Vanadium, which forms a complete series of solid solutions with Fe, exhibited a hardness minimum at approximately 2 at.%. In contrast, hardness minimums were observed in Fe-Nb and Fe-Ta alloys near 0.1 to 0.2 at.%. The solubilities of Nb and Ta in Fe are both less than 0.5 at.%, suggesting that the high hardnesses in

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these alloy systems at 0.5 and 1.0 at.% solute are due to the appearance of hard Fe_2Nb and Fe_2Ta phases, respectively.

The effects of the Groups VI, VII, and VIII solute elements on the hardness of Fe are shown in figures 4 to 8. In most cases, hardness minimums occur between 1 and 4 at.% solute at 77 K in these 13 alloy systems. At 188 K the hardness minimums shift to lower solute concentrations, near 1 at.% in most instances. At the higher temperatures, 300 and 411 K, softening usually was not observed. On a homologous temperature basis for the Fe alloys, 300 K corresponds to 0.166 T_m. Previous results on several binary Mo alloys (ref. 5) as well as Cr-Re and W-Re alloys (ref. 4) have shown that alloy softening does not occur above homologous temperatures of about 0.165. The decrease of solute content at the hardness minimum with increase in temperature and the final disappearance of alloy softening near 0.166 T_m in Fe alloys are in agreement with prior results for the Group VI metals Cr, Mo, and W.

One notable exception to the general hardness behavior exhibited by the binary Fe-Groups VI, VII, and VIII alloys was that of Fe-Cr alloys. As shown in figure 4, a hardness minimum occurs near 8 at.% Cr at 77 K and near 4 at.% Cr at 188 K, much higher solute contents than observed in the other binary Fe-alloy systems. There was also a small decrease in hardness of 3 to 5 VHN, at 300 and 411 K in the Fe - 1 at.% Cr alloy.

The effects of the 19 solute additions on the hardness of Fe at 77 K, where alloy softening predominates, are summarized schematically in figure 9. The results can be characterized by three types of behavior. Fourteen of the solute additions produce initial softening in Fe followed by gradual hardening at solute concentrations past the hardness minimum, which occurs at 1 to 4 at.% solute. The hardness behavior in the Fe-Cr alloy system is similar except that softening extends to a much higher solute content. Alloys containing Nb and Ta additions, however, exhibited slight softening near 0.1 at.% solute followed by rapid hardening. In contrast with these two types of behavior, alloy softening did not occur in binary Fe-Zr and Fe-Hf alloy systems.

Temperature Effects

The dependence of hardness on temperature is shown in figures 10 to 16, where the data are again presented by Periodic Groups. Data for unalloyed Fe are also shown along with those for each of the binary alloys for comparative purposes.

Figure 10(a) presents the data for Fe and Fe-Ti alloys. For unalloyed Fe below 300 K, hardness increases rapidly with decreasing temperature. However, above 300 K, hardness is independent of temperature. This type of behavior in Fe has been described previously by Conrad (ref. 19), where 300 K was identified as the approximate temperature at which the thermal component of the yield stress goes to zero. Our

results show that for unalloyed Fe the temperature dependence of hardness is in agreement with the temperature dependence of yield stress. Additions of Ti to Fe reduce the temperature dependence of its hardness at the lower test temperatures (fig. 10(a)). In contrast, Fe-Zr (fig. 10(b)) and Fe-Hf (fig. 10(c)) alloys exhibit a temperature dependence of hardness quite similar to that for unalloyed Fe. Alloy softening did not occur in these two alloy systems.

Additions of the Group V metals to Fe caused similar behavior, as shown in figure 11. Dilute additions of V to Fe reduced the temperature dependence of its hardness over the 77 to 300 K temperature range (fig. 11(a)). Although additions of 0.10 at.% Nb and 0.17 at.% Ta lowered the hardness of Fe, as in alloy softening, the temperature dependence of hardness was unchanged compared to unalloyed Fe. This occurred because at these dilute levels of Nb and Ta, softening occurred over the entire temperature range, as shown in figures 11(b) and (c). Niobium and Ta additions of nearly 0.5 and 1.0 at.% in Fe produced hardening over the entire temperature range, and the temperature dependence of hardness of these alloys paralleled that for unalloyed Fe.

The effects of adding alloys from Groups VI, VII, and VIII are shown in figures 12 to 16 and are quite similar. All 13 elements shown in these figures reduced the temperature dependence of Fe at the lower test temperatures.

The temperature dependence of Fe and the 19 binary Fe alloys at dilute solute concentrations is summarized schematically in figure 17. Fifteen of the solute additions produced the type of alloy softening that has been observed in other bcc alloys. This behavior is characterized by a reduction in the temperature dependence of hardness, as shown in figure 17. Two solute additions, Nb and Ta, also produced softening, but the softening occurred at all four test temperatures so that the temperature dependence of hardness remained comparable to that for unalloyed Fe. Additions of Zr and Hf did not produce alloy softening in Fe, and the temperature dependence of hardness for binary Fe alloys containing these additions was quite similar to that for unalloyed Fe.

DISCUSSION

Alloy Softening and Hardening

Leslie, in his review of dilute solid solutions of Fe (ref. 1), noted that alloy softening has been observed in 21 different Fe-alloy systems. As a result of our investigation, we can add five more elements (Nb, Ta, W, Os, and Pd) that also produce alloy softening in Fe. We also confirmed that 12 of the elements identified by Leslie (Ti, V, Cr, Mo, Mn, Re, Ru, Co, Rh, Ir, Ni, and Pt) produce softening in Fe. In addition, we identified Zr and Hf as two elements that do not produce alloy softening in Fe.

One of the primary purposes of this investigation was to determine if electron concentration was important in controlling hardness of binary Fe alloys. Analysis of our data failed to reveal any correlation of alloy softening or alloy hardening with the number of s + d electrons contributed by the solute elements (fig. 1). This was not too surprising, since the effect of solute content on the hardness of 14 of the binary Fe alloys was similar (fig. 9), regardless of the Periodic Table Group represented by the solute element.

The schematic representations of the data shown in figures 9 and 17 suggest that the 19 alloy systems studied can be divided into three separate categories. The basis for this separation is the atomic radius ratio of solute to Fe (fig. 1). Atomic radius ratio was used rather than the more conventional lattice parameter change with solute concentration since the latter is not available for many of the alloy systems. The radius ratios of solute to Fe are shown in figure 18 for the elements studied herein. The horizontal dashed lines in the figure represent the ±15 percent size difference limit for favorable solid-solution formation as suggested by Hume-Rothery (ref. 14).

The first category to be considered includes Zr and Hf, those elements that did not produce alloy softening in Fe and did not change the temperature dependence of hardness. Examination of figure 18 shows that these two elements lie well beyond the +15 percent limit for solid-solution formation.

The second category to be considered includes those elements that produced softening at very dilute concentrations followed by rapid hardening, but that did not change the temperature dependence of hardness. Elements in this category include Nb and Ta, which are noted in figure 18 to lie just out of the +15 percent size limit for solid-solution formation. Although Ti has an atomic radius ratio approaching those for Nb and Ta, its hardness behavior did not resemble the behavior noted for this category. The difference in behavior of these three elements is matched by a large difference in solubility. While Nb and Ta have a solubility limit of less than 1 at.%, the maximum solubility of Ti in Fe is nearly 8 at.%.

The remaining category, which comprises 15 of the elements investigated, is characterized by alloy softening at 77 K over solute concentrations to 8 at.% and a reduction in the temperature dependence of hardness. Figure 18 reveals that all 15 elements lie within the ±15 percent limit for solid-solution formation.

Based on these correlations, it appears that atomic size plays a dominant role in controlling hardness in binary Fe alloys. Previous results on Nb-base alloys (ref. 7) have shown that hardening rates could be correlated with atomic size misfit (difference between radii of solute and Fe divided by radius of Fe). Figure 19 presents a correlation of alloy softening rates for the 15 binary Fe-alloy systems with solute-to-iron atomic radius ratios within the ±15 percent size limit. Because alloy softening is most prominent at lower temperatures, softening rates at the lowest test temperature, 77 K,

were used for the correlation. For those elements in figure 19 that have smaller atomic radii than Fe (i.e., Co, Ni, and Mn), a separate correlation exists between softening rates and atomic radius ratios as compared to those elements that have larger atomic radii than Fe. For the 12 elements having larger atomic radii than Fe, good agreement between softening rates and radius ratios exists, with the exception of W and Ti. The correlations shown in figure 19 indicate that atomic size is an important parameter in controlling alloy softening in binary Fe-base alloys.

A similar correlation of hardening rates with atomic radius ratio is presented in figure 20. Because alloy softening is minimal or nonexistent at higher test temperatures, hardening rates at 411 K, the highest test temperature in this investigation, were used for the correlations in figure 20. Those elements with smaller atomic radii than Fe again fit a different relation with radius ratio than those elements with larger atomic radii than Fe. With the exception of Pd, agreement of hardening rates with atomic radius ratios is excellent for 14 of the alloy systems investigated, thus suggesting that atomic size is the primary factor in controlling alloy hardening in Fe. Leslie (ref. 1) concluded that size misfit parameter is a reasonably good indicator of the strengthening of α-Fe by low concentrations of substitutional solutes. In the work by Spitzig and Leslie (ref. 10) on Fe - 3 at.% Co, Ni, or Si alloys, it was suggested that alloy softening at lower temperatures should be most marked in alloys that show pronounced alloy hardening near 295 K. Based on our results of alloy softening at 77 K and alloy hardening at 411 K, this hypothesis is confirmed. For example, Mn exhibits a high hardening rate at 411 K and a high softening rate at 77 K, while for Co both the hardening rate at 411 K and the softening rate at 77 K are relatively small. Our results further confirm that both alloy softening and alloy hardening are controlled by the solute-to-Fe atomic radius ratio or the atomic misfit in 15 of the alloy systems that were investigated. A similar analysis of the data in terms of shear modulus (as reported previously by Leslie (ref. 1)) failed to show a correlation between the softening or hardening rates and the change in shear modulus produced by the solute elements.

Controlling Mechanisms

Alloy softening in Fe has been alternately attributed to lowering of the Peierls or lattice friction stress, to promotion of cross slip, and to scavenging of interstitial impurities. The first two mechanisms are intrinsic effects, while the third mechanism is an extrinsic effect. Based on a study of three alloys, Fe - 3 at.% Co, Ni, or Si, and examination of literature data, Spitzig and Leslie (ref. 10) concluded that the controlling mechanism for alloy softening in Fe alloys was a decrease in the lattice friction stress as a result of solute atoms nucleating kinks on screw dislocations, an intrinsic effect.

The other mechanisms proposed did not fit their experimental data. Based on the results of our study of 19 binary Fe alloys with similar impurity levels, we conclude that alloy softening is an intrinsic effect in most cases. Alloy softening observed for 15 alloy systems (whose atomic radii were within the ±15 percent size limit for solid-solution formation) was characteristic of an intrinsic effect and similar to alloy softening observed in the Group VI bcc metals Cr, Mo, and W (refs. 4 to 6). These characteristics include the following:

(1) Alloy softening is more marked at lower temperatures and disappears at higher temperatures.

(2) The temperature dependence of hardness is lowered by those elements that produce alloy softening.

(3) Alloy softening at the lowest test temperature reaches a minimum in hardness at a relatively high solute concentration from 1 to 4 at.% solute in most cases and as high as 8 at.% for Cr at 77 K.

Based on the similarity of the effects of atomic size in our results and those observed by Spitzig and Leslie (ref. 10), we conclude that the probable mechanism of alloy softening in these 15 alloy systems is lowering of the lattice friction stress.

The exception to this mechanism is the alloy softening observed with very dilute additions, nearly 0.1 at.%, of Nb and Ta. Alloy softening in these two Fe-alloy systems did not meet any of the characteristics noted for intrinsic alloy softening. Softening occurred over the entire temperature range, the temperature dependence of hardness was not lowered in these alloys but paralleled unalloyed Fe, and softening occurred at only very low solute concentrations. Based on these results, we suggest that alloy softening in Fe-Nb and Fe-Ta alloys arises as a result of the solute atoms scavenging interstitial impurities, an extrinsic mechanism. The results suggest that very dilute additions of Nb or Ta may be better getter additions to Fe than Ti since, at dilute concentrations of Nb and Ta, hardness is not complicated by hardening at the higher test temperatures

The theories proposed to describe alloy hardening in metals normally involve a size misfit parameter and a shear modulus parameter (refs. 1 and 20). The good agreement of hardening rates with atomic size in 15 of our alloy systems suggests that atomic size may be the primary factor of importance. Shear modulus difference may be of only minor importance in these binary Fe alloys since hardening rates could not be correlated with change in shear modulus. The rapid rise in hardness observed in Fe alloys containing Nb, Ta, Zr, and Hf may arise from formation of intermetallic compounds rather than because of the high atomic radius ratios.

CONCLUSIONS

Based on a study of the hardness behavior of 19 binary iron-alloy systems, the following conclusions are drawn:

1. Atomic radius ratio of solute to iron plays a dominant role in controlling the hardness behavior of binary iron alloys.

2. Alloy softening rates at 77 K and alloy hardening rates at 411 K can be correlated with the atomic radius ratio of solute to iron for 15 of the binary iron-alloy systems. These 15 solutes lie within the ±15 percent size limit suggested by Hume-Rothery for favorable solid-solution formation and include Ti, V, Cr, Mo, W, Mn, Re, Ru, Os, Co, Rh, Ir, Ni, Pd, and Pt.

3. Alloy softening in these 15 alloy systems is due to an intrinsic mechanism. Similarities between our results and previous literature results suggest that lowering of the Peierls stress by solute atoms aiding kink formation on screw dislocations may be the controlling mechanism. Also, alloy hardening in these 15 alloy systems is due primarily to an intrinsic mechanism, atomic size misfit, rather than to shear modolus difference.

4. Alloy softening occurs in binary Fe-Nb and Fe-Ta alloy systems as a result of an extrinsic mechanism, believed to be scavenging of interstitial impurities.

5. Alloy softening does not occur in binary Fe-Zr and Fe-Hf systems because of the very large solute-to-iron atomic radius ratios.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, November 17, 1975,
            506-16.

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TABLE I. – CHEMICAL ANALYSIS AND SUMMARY OF HARDNESS DATA FOR BINARY IRON ALLOYS

Element	Analyzed solute content, at.%	Analyzed interstitial content, ppm by weight			Vickers hardness number (VHN) at temperature of –				Element	Analyzed solute content, at.%	Analyzed interstitial content, ppm by weight			Vickers hardness number (VHN) at temperature of –			
		C	O	K	77 K	188 K	300 K	411 K			C	O	K	77 K	188 K	300 K	411 K
Fe	100	66	120	6	226	127	60	60	Ru	0.99				221	112	82	78
Ti	1.02	56	92	7	223	103	93	85		1.71	13	154	19	194	113	92	86
	2.08				210	140	117	102		3.61				218	143	123	107
	3.86	87	94	9	207	175	152	138		7.71	23	133	18	254	227	209	187
	8.12				366	305	286	253	Rh	1.31				228	112	90	85
V	1.09				214	119	63	57		2.01	20	175	22	202	129	103	98
	2.14	32	26	31	205	113	64	61		4.18				209	135	123	113
	4.30				217	119	77	75		8.06	12	133	19	237	183	159	149
	8.34	168	30	124	230	131	110	100	Pd	1.04	14	186	32	202	133	111	100
	16.6				268	194	168	159		2.08				220	171	148	135
Cr	0.99				209	116	57	55		3.95	10	171	36	280	239	204	178
	1.98	50	30	12	202	119	67	66	Hf	0.10	33	77	14	318	216	153	154
	3.92				163	110	66	64		.32	51	102	32	312	218	150	153
	7.77	40	85	10	157	117	82	74		.54	26	82	12	312	214	162	154
	16.2				165	129	111	96	Ta	0.17	34	86	18	213	121	59	47
Mn	0.49				203	110	61	61		.39				267	165	118	105
	.96	39	65	6	189	91	75	67		1.05	22	92	22	290	170	131	108
	1.96				190	105	87	79	W	0.83	30	140	12	230	134	102	84
	3.93	32	134	8	210	164	140	129		1.32				208	125	122	89
	7.59				281	238	209	205		3.46	23	61	21	236	189	152	138
Co	0.99				223	129	63	63		6.66				304	233	190	179
	1.90	110	164	12	206	121	63	61	Re	0.77	34	72	18	211	124	75	72
	3.78				214	120	72	70		1.39				201	117	89	81
	7.49	62	66	5	218	118	75	74		3.90	44	72	21	191	139	117	102
	14.9				233	133	113	105		6.29				238	209	175	156
Ni	0.51				220	107	66	63	Os	0.40				196	105	75	72
	1.03	28	90	6	201	96	75	71		1.37	31	85	18	187	113	89	81
	2.10				181	102	91	85		3.78				195	138	117	111
	4.02	48	24	5	188	135	112	103		8.09	41	87	25	301	267	235	229
	8.02				205	181	160	148	Ir	0.83	36	146	21	217	129	80	77
	15.7	38	49	7	288	262	228	220		1.73				203	123	92	87
Zr	0.10	33	141	14	317	191	140	130		3.45	21	68	14	208	141	121	111
	.22				317	192	143	126		7.76				223	185	165	153
	.47	33	171	15	293	200	144	131	Pt	0.74	62	83	24	206	111	88	82
Nb	0.10	37	178	24	215	106	63	53		1.50				187	129	108	96
	.48				242	141	115	107		3.08	46	36	17	190	151	133	125
	.95	24	184	19	282	171	125	112		6.68				228	190	162	143
Mo	1.02	37	176	16	202	133	82	82									
	2.00				205	145	104	96									
	4.03	21	167	14	205	162	140	127									
	7.92				263	246	208	188									

Period	Group							Reading key
	IV	V	VI	VII	VIII			
Fourth	22 d^2s^2 Ti 1.1476	23 d^3s^2 V 1.0565	24 d^5s^1 Cr 1.0063	25 d^5s^2 Mn 0.9434	26 d^6s^2 Fe 1.0000	27 d^7s^2 Co 0.9827	28 d^8s^2 Ni 0.9780	Atomic number — Bonding electrons; 26 d^6s^2 Fe 1.0000 — Element; — Radius ratio
Fifth	40 d^2s^2 Zr 1.2575	41 d^4s^1 Nb 1.1523	42 d^5s^1 Mo 1.0989	43 d^6s^1 Tc 1.0714	44 d^7s^1 Ru 1.0637	45 d^8s^1 Rh 1.0557	46 d^{10} Pd 1.0801	
Sixth	72 d^2s^2 Hf 1.2402	73 d^3s^2 Ta 1.1515	74 d^4s^2 W 1.1052	75 d^5s^2 Re 1.0793	76 d^6s^2 Os 1.0798	77 d^7s^2 Ir 1.0651	78 d^8s^2 Pt 1.0887	

Figure 1. – Partial Periodic Table showing solute elements alloyed with iron for this investigation.
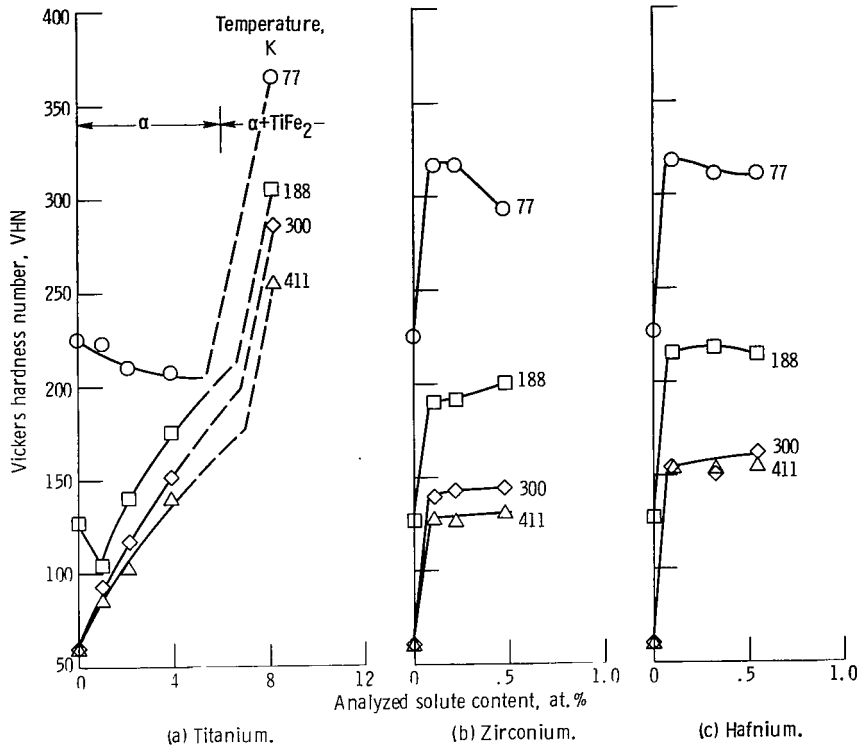
13

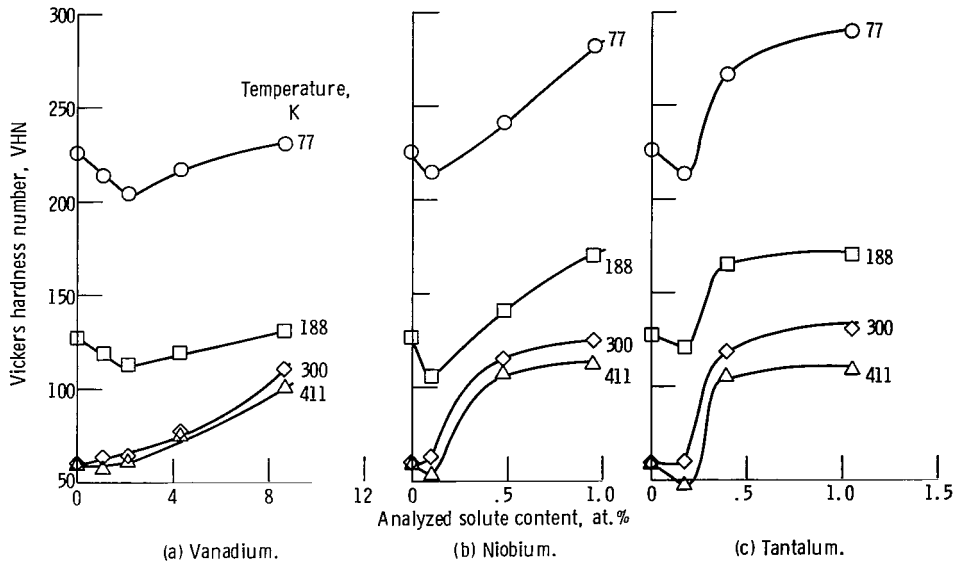Figure 2. - Effect of Group IV elements Ti, Zr, and Hf on hardness of binary iron alloys.

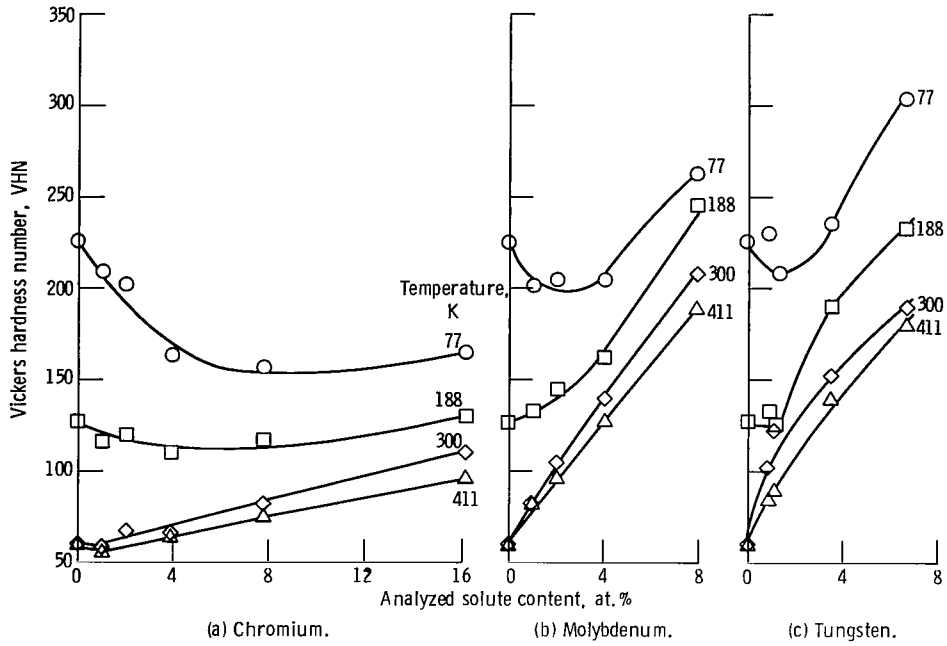Figure 3. - Effect of Group V elements V, Nb, and Ta on hardness of binary iron alloys.

14

Figure 4. – Effect of Group VI elements Cr, Mo, and W on hardness of binary iron alloys.
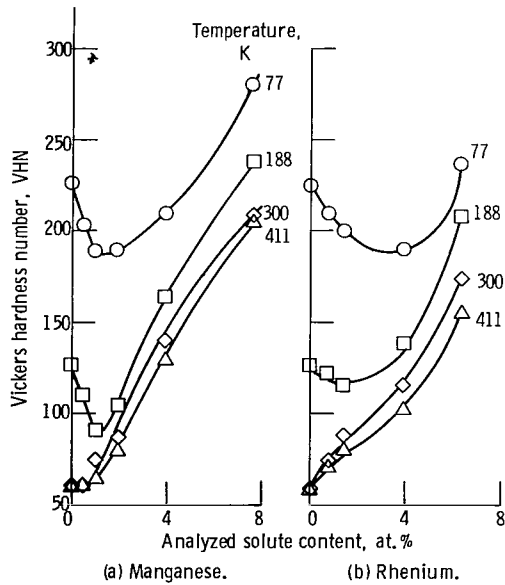

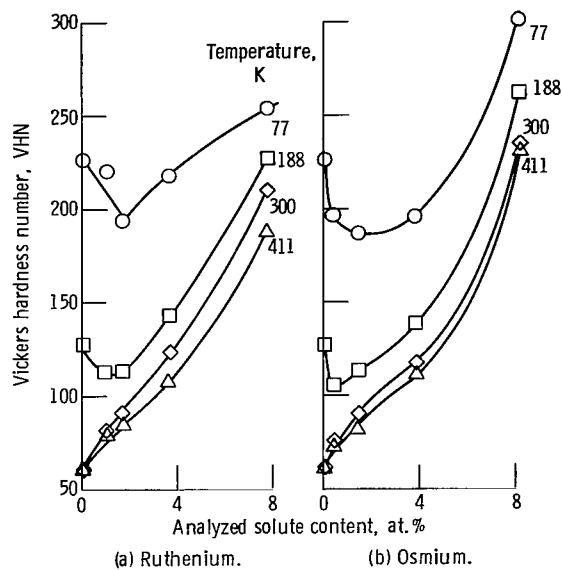Figure 5. – Effects of Group VII elements Mn and Re on hardness of binary iron alloys.

15

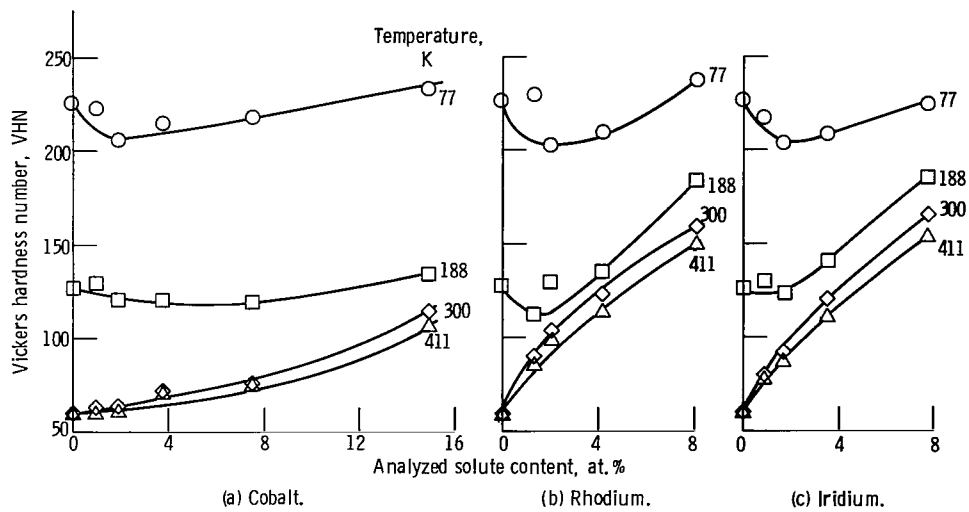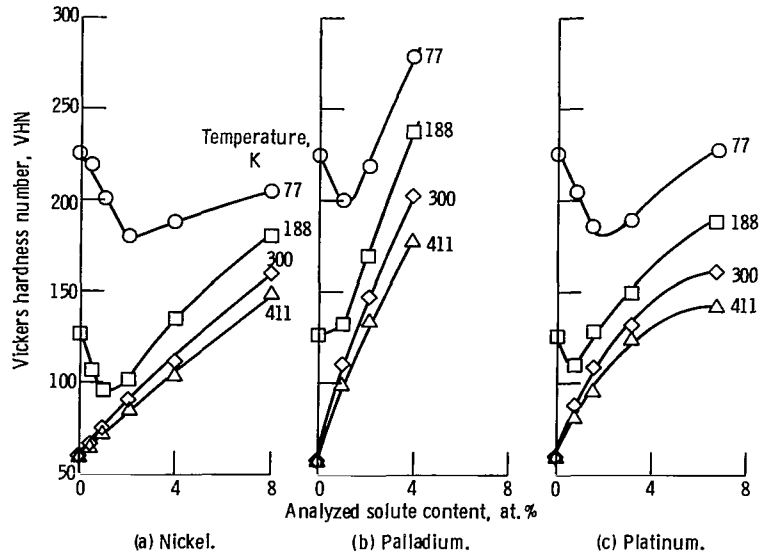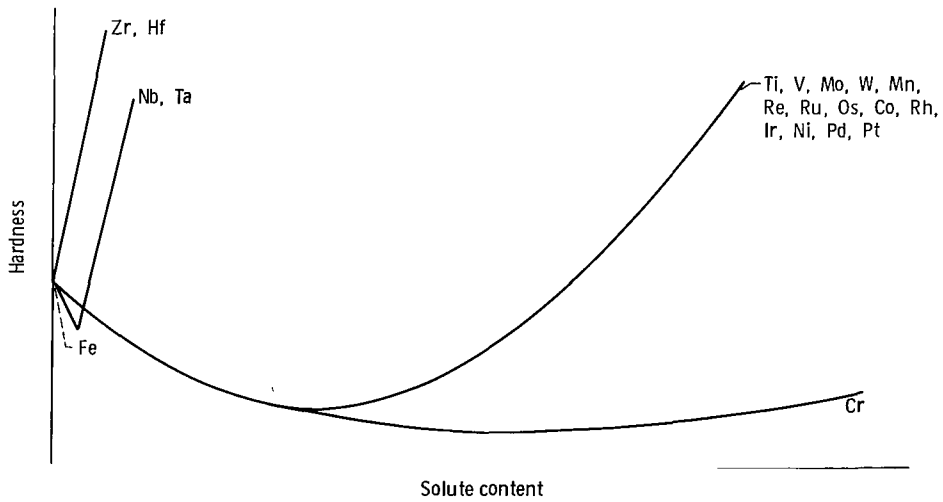Figure 6. - Effects of Group VIII elements Ru and Os on hardness of binary iron alloys.

Figure 7. - Effects of Group VIII elements Co, Rh, and Ir on hardness of binary iron alloys.

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(a) Nickel. (b) Palladium. (c) Platinum.

Figure 8. - Effects of Group VIII elements Ni, Pd, and Pt on hardness of binary iron alloys.

Figure 9. - Schematic representation of solute effects in binary iron alloys at 77 K.

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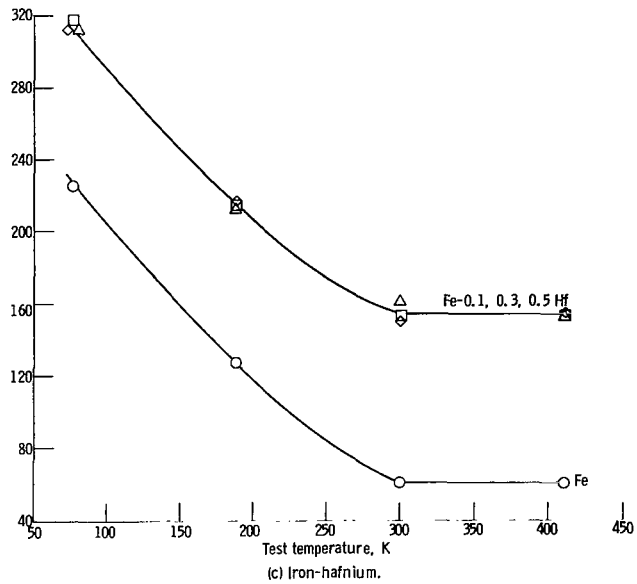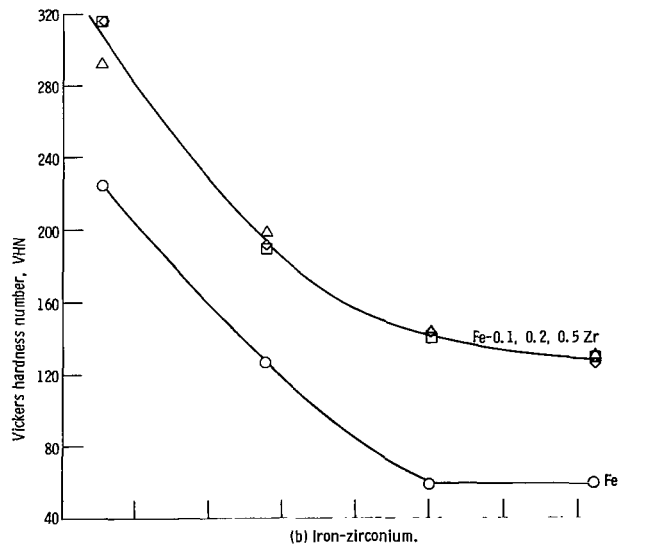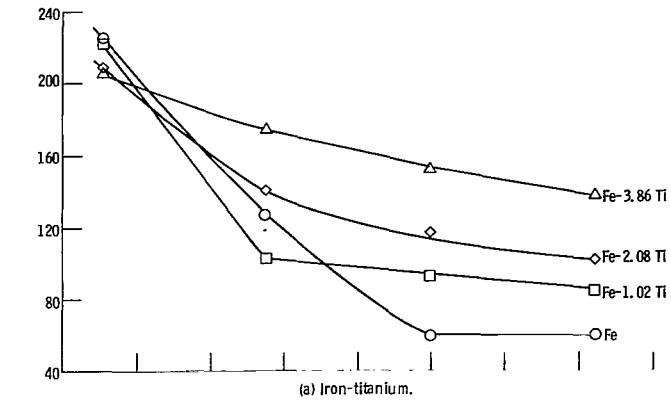
Figure 10. - Effect of test temperature on hardness of binary alloys of iron and Group IV elements Ti, Zr, and Hf.

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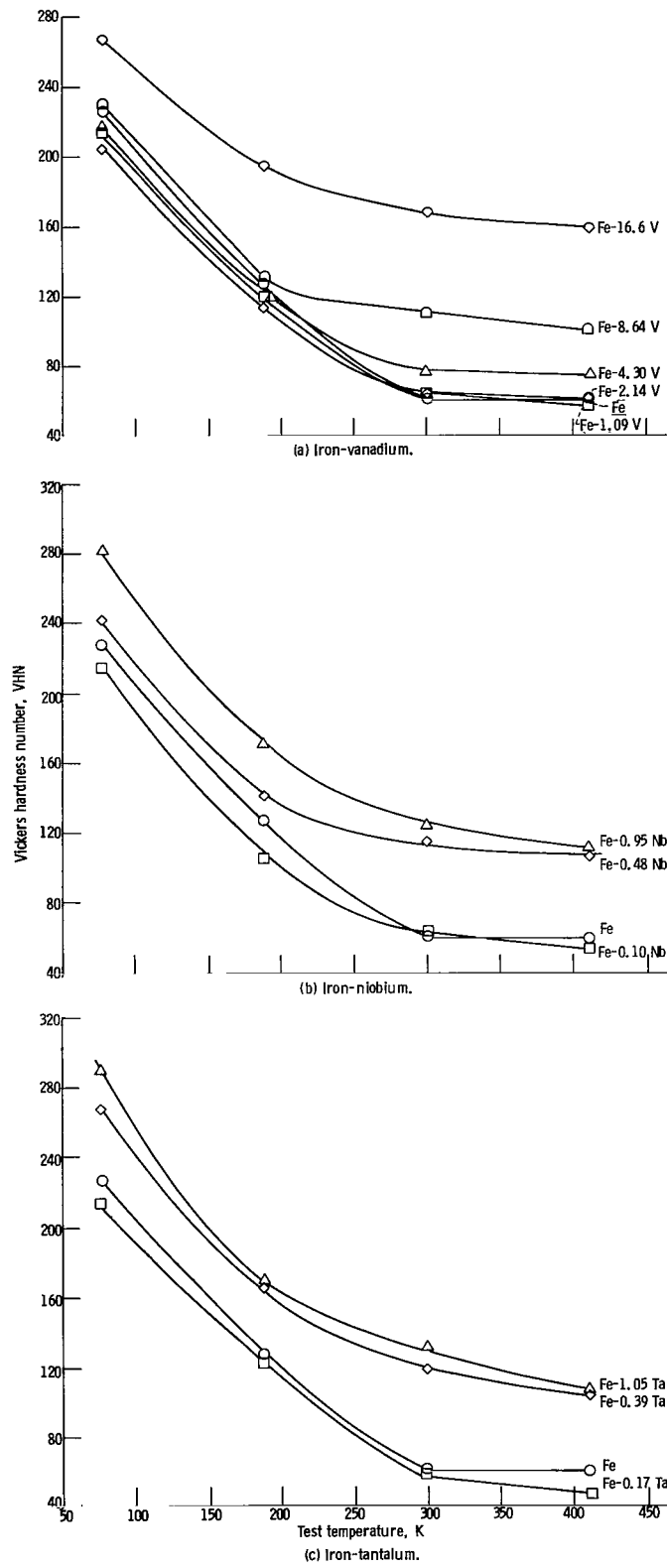
Figure 11. - Effect of test temperature on hardness of binary alloys of iron and Group V elements V, Nb, and Ta.

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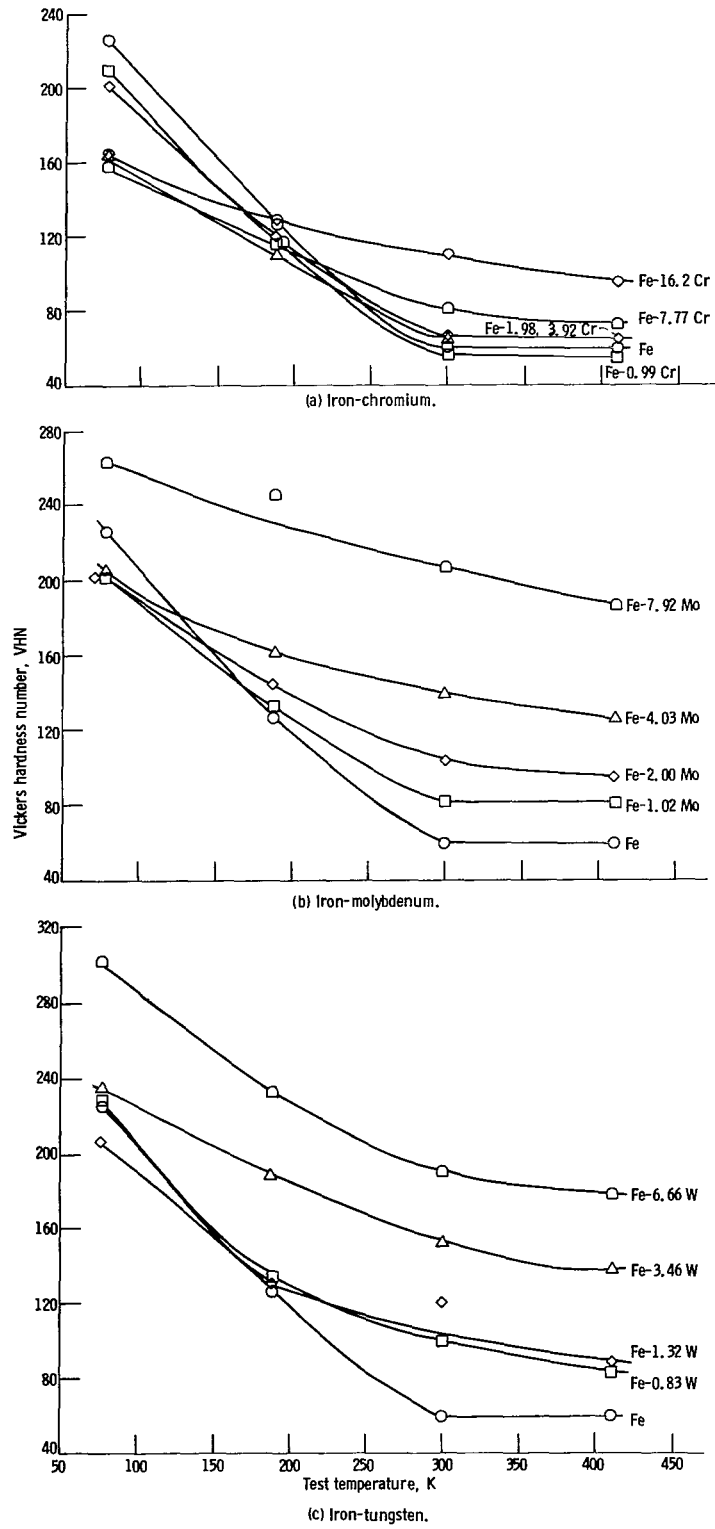
Figure 12. - Effect of test temperature on hardness of binary alloys of iron and Group VI elements Cr, Mo, and W.
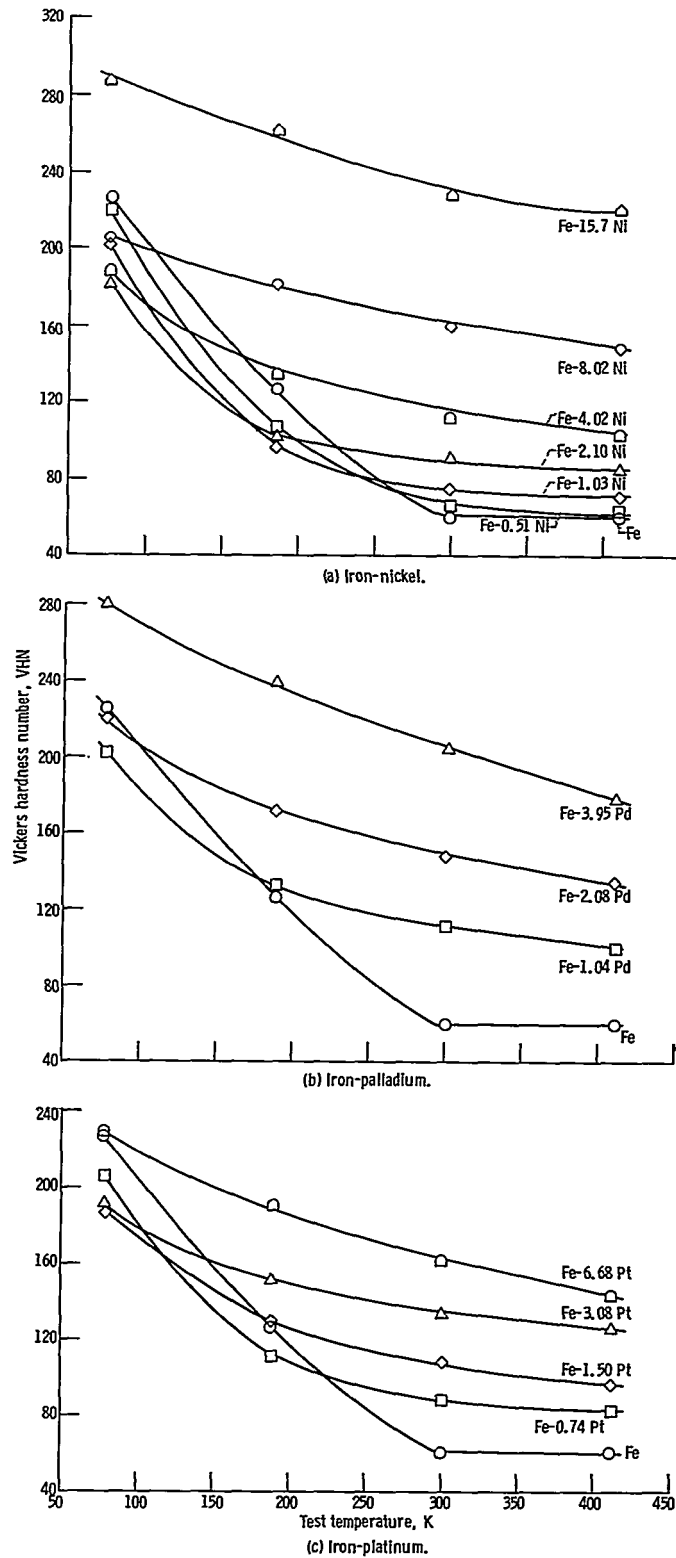
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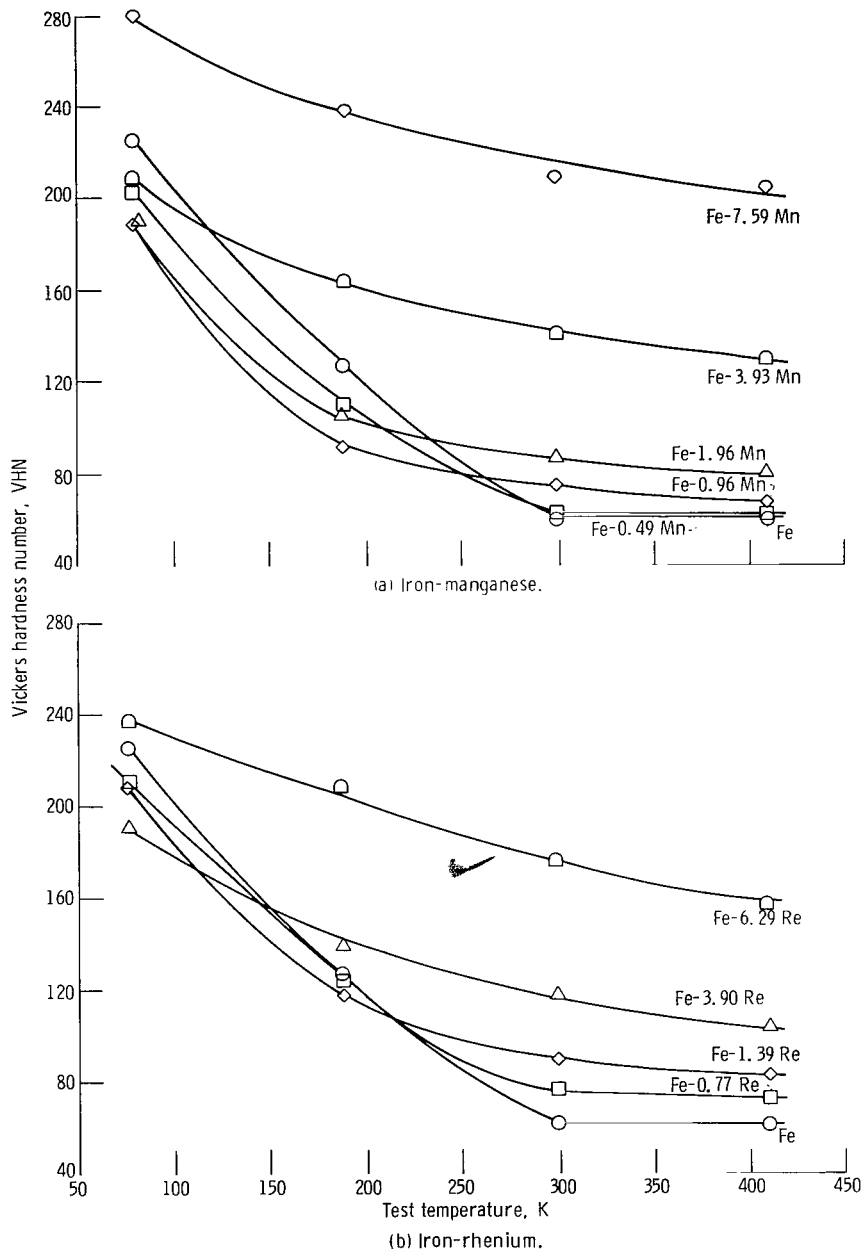
Figure 13. - Effect of test temperature on hardness of binary alloys of iron and Group VII elements Mn and Re.

21
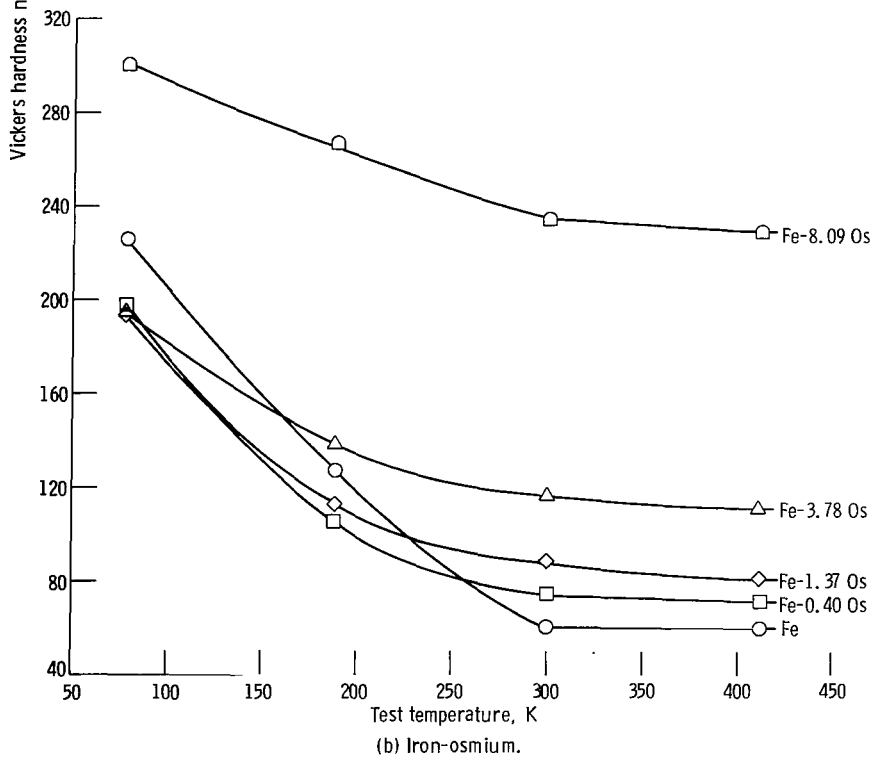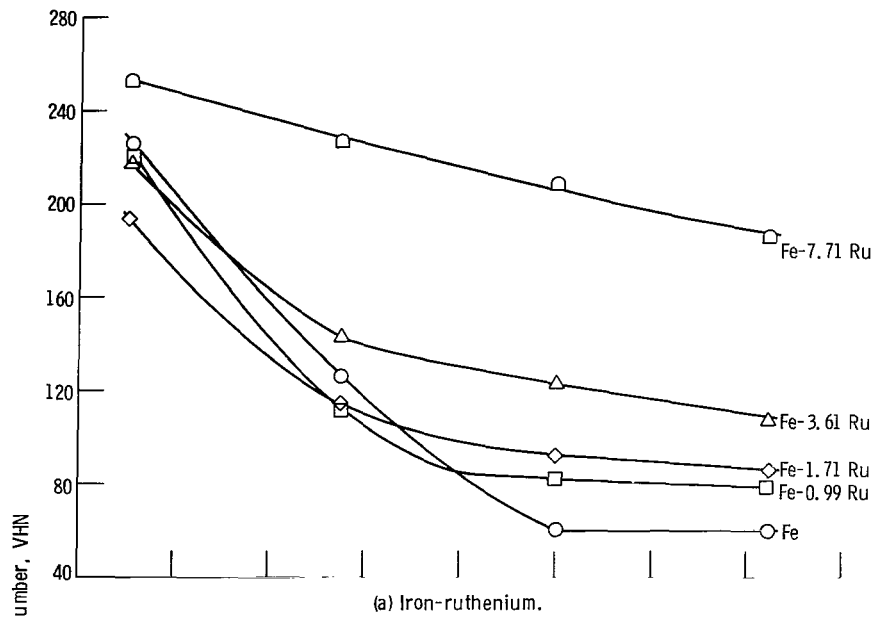
Figure 14. - Effect of test temperature on hardness of binary alloys of iron and Group VIII elements Ru and Os.
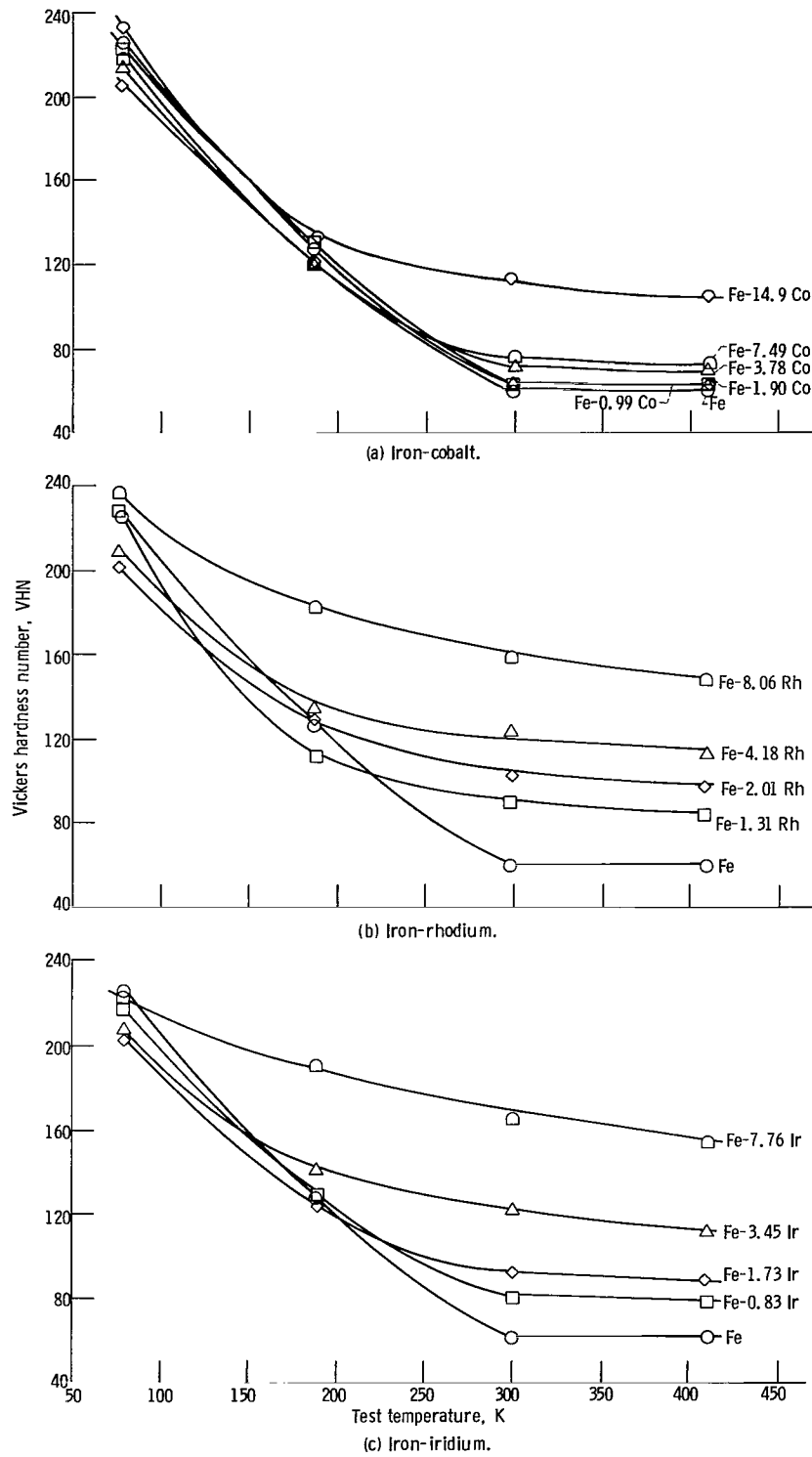
Figure 15. – Effect of test temperature on hardness of binary alloys of iron and Group VIII elements Co, Rh, and Ir.

Figure 16. – Effect of test temperature on hardness of binary alloys of iron and Group VIII elements Ni, Pd, and Pt.
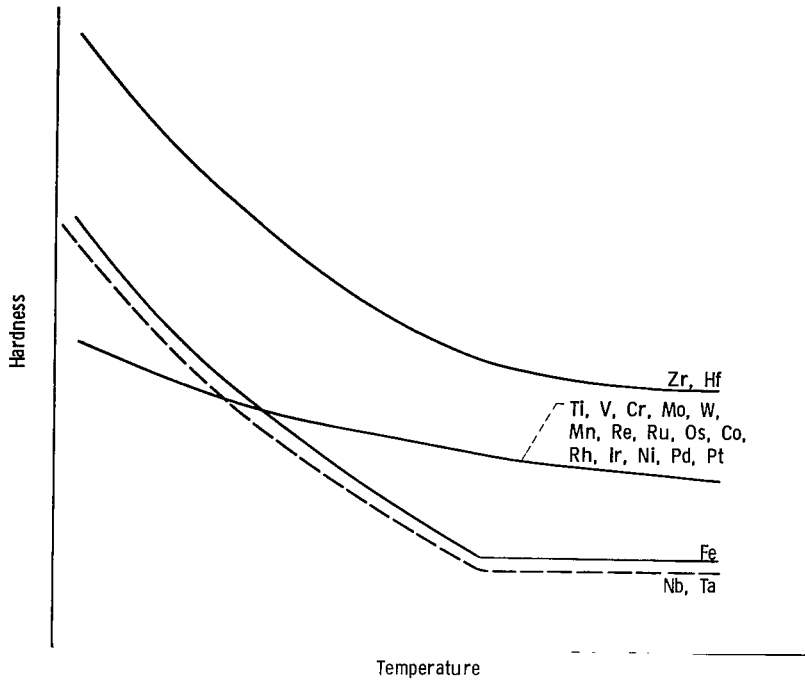
Figure 17. - Schematic representation of the temperature dependence of hardness of un-
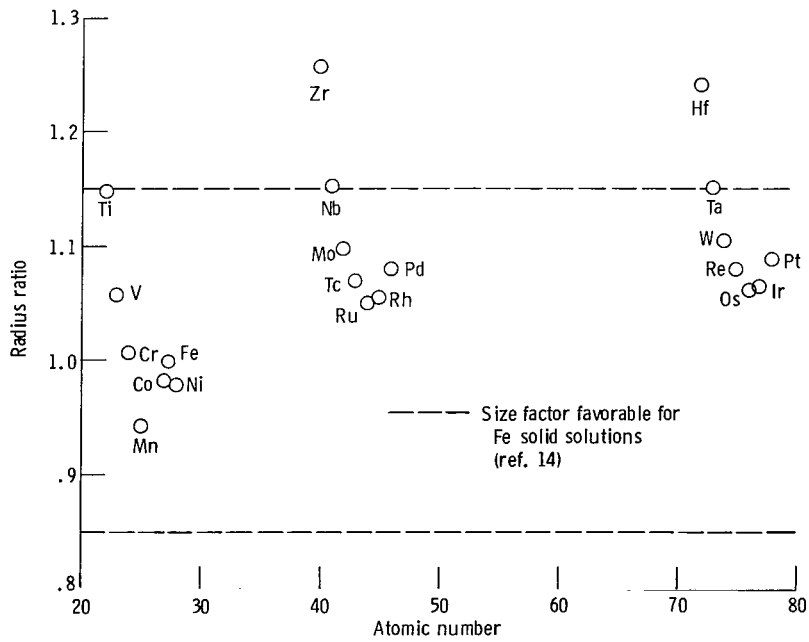alloyed iron and binary iron alloys.

Figure 18. - Atomic radius ratio of 19 solute elements to iron and range for solid-
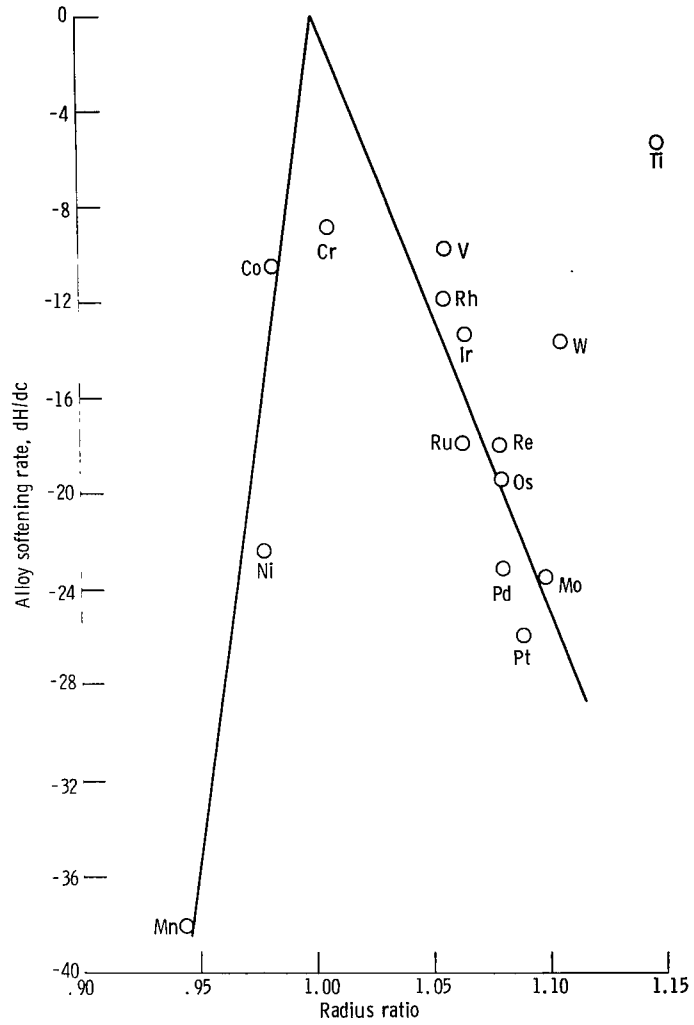solution formation based on a radius ratio not to exceed ±0. 15.

Figure 19. - Correlation of alloy softening rates at 77 K with solute-to-iron atomic radius ratio for binary iron-base alloys.
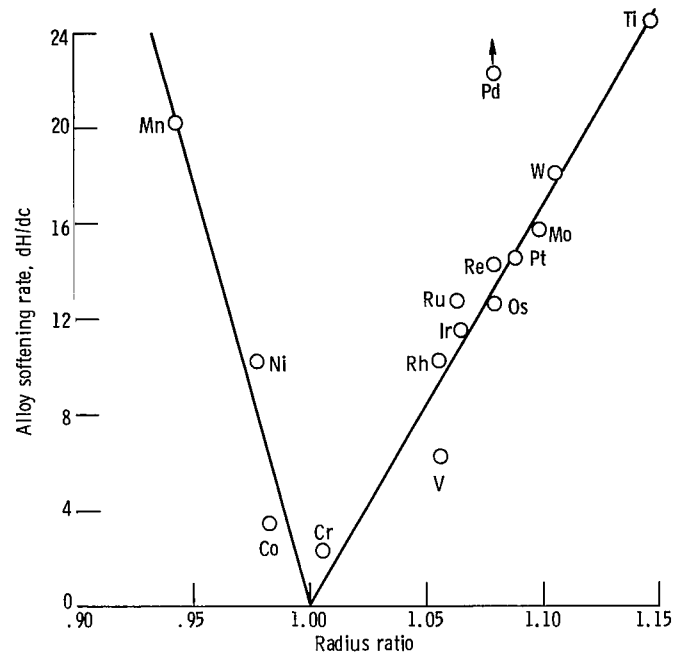

Figure 20. - Correlation of alloy hardening rates at 411 K with solute-to-iron atomic radius ratio for binary iron-base alloys.

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