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R&D AND EVALUATION OF A LIGHTWEIGHT, HIGH STRENGTH MAGNESIUM ALLOY

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ABSTRACT

A six pound melt of Mg-30Sc was successfully prepared, cast into a 3" diameter billet, and extruded into 1/16" X 1 1/4" strip. Quenching the strip as it emerged from the extrusion press caused severe cracking. The β content of the extrusion was significantly higher at the center of the cross-section and at the nose of the strip than at the surface and butt. In spite of this apparent segregation of Sc, the extrusion had excellent properties-14.5% elongation, 52ksi yield strength, and 58ksi tensile strength-whether it was quenched or not. Modulus ($\sim 7X10^6$psi) was lower than that determined previously.

Four additional ternaries were evaluated on the mini-scale but offered no improvement over the alloys developed in previous work.

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INTRODUCTION

The microstructure and properties of Mg-Sc binaries and ternaries were determined on a mini-scale during the first year of this project. This work indicated that Mg-Sc alloys offer mechanical properties far superior to those of any Mg alloy yet developed. Of particular interest was Mg-30Sc, which provided high strength (50-60ksi yield), high modulus (8-9 X 10^6psi), adequate ductility (7-11%E), and good high temperature properties. Ternary additions such as Li, Ag, and Cd improved the properties of Mg-Sc and provided high strength at lower Sc levels. Mg-10Sc-5Li, for example, offers a yield strength of 50ksi, and even higher strength can be obtained with Mg-20Sc-6Ag.

The purpose of the current work is the evaluation of the most promising Mg-Sc alloys on a normal laboratory scale. Extrusion of the alloys into 1/16" X 1 1/4" strip will permit the use of standard test bars and more extensive testing. Mg-30Sc will be evaluated in this manner, while additional ternary alloys are studied on a mini-scale. When the optimum composition of the ternaries has been determined, they will then be studied on the larger scale.

EXPERIMENTAL WORK

A Mg-30Sc billet 3" in diameter and about 6" long was prepared. Pure Mg (almost 4 lbs.) was first melted in an alumina crucible supported in a steel can. A low density flux (containing mostly KCl and a small amount of $MgCl_2$) was selected for melt protection because it floats on the metal and is less likely to contaminate the casting. When the melt temperature exceeded 1450F, most of this flux was skimmed off (to remove $MgCl_2$) and was replaced with KCl. The Sc ($\sim$ 2 lbs.) was then added to the melt.

The Sc discs (about 4" in diameter and 1/2" thick) were too massive as-received to permit ready dissolution. They were therefore cold-rolled sufficiently to break them up into small pieces. The melt was heated to about 1870F and held while the Sc gradually dissolved. Most of the Sc dissolved within 2.5 hours, but an additional hour was used to insure complete dissolution. Most of the melt was then bottom poured into a 3" diameter billet mold. The remainder of the melt (equal to about one inch of billet) was top poured to cap the casting. The top 1/4" of the billet and the gate were sawed off, and the billet was scalped. It was then preheated for one hour at 900F and extruded into 1/16" X 1 1/4" strip at 10 feet per minute from the 3" container (also at 900F) of the 500 ton Watson-Stillman press.

A few ternary alloys were also evaluated on a mini-scale. Melts of 50-100 grams were prepared in an alumina crucible and cast in a 3/4" diameter mold. Billets cut from the casting were scalped and extruded on a miniature extrusion press into 1/8" diameter wire.

DISCUSSION

A) Mg-30Sc

1) Casting

For the first time, a Mg-Sc alloy was processed on a normal laboratory scale. Mg-30Sc was cast into a 3" diameter billet about 6" long, which was extruded into 1/16" X 1 1/4" strip. Casting the alloy was particularly difficult because of its high liquidus temperature ($\sim$ 1675F) and the potential reaction of Sc with a graphite crucible and the $MgCl_2$ in flux. Since we also wished to avoid iron contamination and its probable adverse effect on corrosion resistance, we selected an alumina crucible instead of an iron pot. To avoid loss of the metal in case of failure of the ceramic, the crucible was placed in a steel jacket. Although heat transfer was impeded by this arrangement, we were able to reach a melt temperature of about

1870F, which was high enough to dissolve the Sc and make the casting. A flux containing a small amount of $MgCl_2$ was used only in the melting of the Mg. When the temperature of the molten Mg exceeded the melting point of KCl (about 1450F), this flux was removed and replaced with KCl.

These special precautions resulted in a successful casting. Visual examination (Fig. 2) indicated a sound casting with somewhat heavier oxidation than usual. The top of the billet apparently solidified too rapidly to fuse readily with the metal added to cap the casting. This resulted in a lap or small cavity at the periphery of the billet. Examination of the crucible indicated that the alumina did crack badly at the bottom but was held intact by the steel jacket. Evidence of reaction of the melt with the ceramic was noted only where the metal filled the cracks in the crucible. Metallographic examination of a cross-section through the gate revealed a cast structure very similar to that of the small Mg-30Sc casting ($\sim$ 50 grams) prepared in the initial work. Furthermore, heat treatment at 950F and 1300F produced completely α (Mg-Sc solid solution) and completely β (Sc-Mg solid solution) structures, respectively. The opportunity of evaluating both phases in a single alloy was a primary consideration in the selection of Mg-30Sc. Chemical analysis revealed a Sc content of 31.4%, which represents a scandium alloying efficiency of $\sim$90%. This is somewhat higher than that experienced in the alloying of rare earths in Mg at much lower temperatures.

2) Extrusion

The Mg-30Sc billet was extruded into 1/16" X 1 1/4" strip at 900F and 10fpm with a maximum pressure of 380 tons (54tsi). The high temperature required for extrusion indicates that Mg-30Sc has relatively high strength at elevated temperatures. In fact, the extrusion conditions used for this alloy are comparable to those required for HM31A (Mg-3Th-1.5Mn), the strongest known Mg alloy at high temperatures. The first part of the push was complicated by severe die loading. A small metallic particle lodged in the die land and almost eliminated metal flow in this area. The press was stopped, the die was cleaned, and metal from the top center of the billet ($\sim$1" diameter cone, $\sim$1" deep) was machined away to remove hard particles that might have been entrapped in the pipe area. Extrusion then proceeded without incident. About 40 feet of strip with a fairly good surface (Fig. 3) was obtained. The last half of the strip was water quenched as it emerged from the press by passing it through a spray chamber about 6" from the die. A few minutes after the push was completed, cracks were noted in the quenched part of the extrusion. In fact, distinct "pings" were heard as the cracking occurred. Some of the cracks occurred only in the core and were revealed by "dimpling" of the surface. Most of the cracks extended to the extrusion surface and edge. Some of the cracks propagated longitudinally down the center of the strip. By the next day some of these longitudinal cracks were over a foot long (Fig. 2). Later metallographic examination showed that the fractures were mostly intergranular except near the surface, where ductile, transgranular failure occurred. Cracking of the quenched strip is puzzling. The strip was quenched in an attempt to inhibit decomposition of β during normal cooling in order to increase strength by subsequent aging. The quenched extrusion is, in fact, quite ductile. A tensile bar taken from an apparently sound area of the strip had an elongation of 14.5%, and another part of the quenched strip was bent back and forth (longitudinally) several times without fracturing. Why, then, did the strip crack?

The first thought was that a phase change or some natural aging (causing brittleness) might be occurring immediately following the quench. We examined this hypothesis by taking a sample of the quenched strip, heating it to 1000°F (estimated exit temperature of the extrusion), quenching the strip in water and then measuring hardness after various holding times at room temperature. No change in hardness was detected (Table 1(A)), thus indicating that the quenched material was stable at room temperature. Stress corrosion was also ruled out as the cause of cracking since most of the cracks apparently began internally.

The most probable cause of the cracking appears to be localized straining induced by the quench. This quenching unit is known to significantly distort extruded strips of other Mg alloys. If the localized straining occurred before the alloy was quenched to room temperature, decomposition of β (particularly at grain boundaries), embrittlement, and cracking could result. The delay before the cracking was observed (and heard) must then be attributed to time for propagation of the internal cracks through the ductile surface. Why the cracking should initiate at the core is clarified by metallographic examination of the strip and hardness tests (Table 1(B)). The core of the strip (and presumably that of the billet) contains significantly more β (and hence Sc) than the surface or the edge. The β content is also much higher at the nose than at the butt. Decomposition of β would therefore tend to embrittle the core far more than the surface. There are, in fact, localized areas in the core which apparently contain so much Sc that they were only partially deformed by working at 900F. Some of these stringers were cracked transversely during extrusion, indicating that they have limited ductility even at 900F. Propagation of some of the cracks down the middle of the extrusion-the area of highest Sc concentration-also appears logical.

3) Properties

The limited amount of strip available for the extensive testing we planned has necessitated careful allocation. At this point tensile properties only in the F temper (as-extruded) have been obtained. These are shown on the following page.

		10^3psi			10^6psi
Quenched?	%E	TYS	CYS	TS	Modulus
No	14	53	53	59	7.5
Yes	14	52	52	56	6.7

These results indicate an excellent combination of strength and ductility. Although the modulus of Mg-30Sc appears to be higher than that of Mg, these values are much lower than those obtained from 1/8" diameter wires in the initial work. The good ductility of the quenched strip indicates that quenching had no effect on the bulk properties of the alloy although it may have embrittled it locally.

Hardness tests have been used to determine the effect of heat treatment conditions on the properties of the Mg-30Sc strip. The optimum thermal treatments determined from this data will be used in the evaluation of tensile properties in various tempers. The results obtained thus far (Table 1) indicate considerable scatter, which decreases the significance of the apparent effects. As shown in Figure 1, aging at 450F hardens the quenched part of the extrusion much more than the air-cooled part. Aging at 350F and 400F is less effective. Solution heat treatment at 950F or 1250F and quenching to produce α or β, respectively, decreases hardness to about the same level ($\sim$40 R_B). Subsequent aging at 450F has little effect on the hardness of α, but markedly hardens β ($\sim$84R_B). It is interesting to note that varying time at 450F from 1 to 46 hours has no effect.

B) Mg-Sc Ternaries

Four additional ternaries were evaluated on a mini-scale. Three of these (Mg-10Sc-3Li, Mg-20Sc-9Ag, and Mg-20Sc-20Cd) are modifications of the most promising ternaries discovered in the initial work. The fourth (Mg-10Sc-12Y) was made in order to evaluate a ternary with enough Y to be age hardenable. As shown in Table 2, the properties of the ternaries were not improved by these compositional changes and were actually decreased in some cases. In spite of the larger Y addition, the Mg-10Sc-12Y ternary actually contained about the same amount of Y as those made previously and must be redone. The quality of the Mg-20Sc-20Cd was so poor that little can be concluded from these results, and this alloy must also be remade. Metallographic examination of Mg-20Sc-9Ag indicates that the higher Ag content produced a larger amount of second phase, which could not be completely dissolved at 950F. We hoped to increase the amount of β by increasing the Ag content, but this apparently did not happen. The effect of heat treatment conditions on this alloy will be studied. The structure of Mg-10Sc-3Li appears to be essentially α - not the β obtained at 5% Li. This explains the lack of hardenability. Solution temperatures higher than 950F may be required for β formation at the lower Li level. This will be checked.

TABLE 1

Hardness (Rockwell- B) of the Mg-30Sc Extrusion

(1/16" X 1 1/4" Strip)

A) Effect of Natural Aging

Quenched?	Solution Temp.	Solution Time	Aging Time	Hardness (R_B)
Yes	None	--	~ 1 hr.	55,56,68,60,62,62,63
			~16 hrs.	60,63,62,64,65
			~11 days	59,61,61,63,63,63
No*	None	--	~ 4 days	63,67,68,72
	1000F	~1 min.	<1 min.	65,65,67
			2	58,60,67
			13	54,60,66
			23	60,63,67,67
			33	60,64,64,66

B) Hardness Transverse Across Width at Nose

↑ 56,57,57,59,63,64,67,67,65,64,62,59,59,57,54,50 ↑

(Edge) (Center) (Edge)

*Sample taken at Nose (like B)

C) Effect of Solution Temperature

(Quenched and Aged at 450F)

Heat Treated at 950F

Aging Time	Hardness
--	37,39,41
1 hr.	39,39,41
2	36,38,39
4	37,42,45
8	41,41,42
16	37,38,41
24	37,38,41
29	34,36,36
40	32,38,41

Heat Treated at 1250F

Aging Time	Hardness
--	42,42,44
1 hr.	82,83,84
2	83,84,86
4	83,84,86
8	82,84,84
24	84,85,86
30	83,83,84
46	84,84,86

TABLE 1 continued

D) Effect of Artificial Aging

Quenched						Not Quenched	
350 F		400 F		450 F		450 F	
Time	Hardness	Time	Hardness	Time	Hardness	Time	Hardness
		—	58,59,60,63				
—	62,63,63	1 hr.	66,66,67	15 min.*	70,70,72,74,74	—	61,62,62
1 hr.	66,67,68	2	66,68,69	1 hr.	73,73,73	1 hr.	64,64,66
2	63,67,67	4	69,71,72	2	76,76,77	2	63,64,65
3	64,66,69	7	71,72,7[illegible]	3	73,74,76	3	61,64,65
4	67,68,70	11	70,74,75	3.5*	71,71,71	4	63,63,65
6	65,66,68	15	71,73,73	4	73,74,74	8	64,65,66
7.5	67,69,70	27	71,71,74	8	74,74,77	16	66,67,68
11	68,68,69			9*	70,71,73,73,74	24	65,65,67
14	68,69,71			16	72,73,75	40	66,67,68
20	67,69,71			24	69,71,73		
24	67,68,71						
36	66,67,67						

*Sample taken at a different location than others in this group.

TABLE 2

PROPERTIES* OF Mg-Sc TERNARIES

		F					CYS				
								T6			
Alloy No.	Composition	%E	TYS	CYS	TS	E	T4	300	350	400	450
101,773	Mg-10Sc-3Li	6	36	35	44	8.2	26	29	29	28	23
101,774	Mg-20Sc-9Ag	5	52	52	59	8.6	42	49	49	42	43
101,775	Mg-20Sc-20Cd	--	--	--	45	10.4	36	37	39	36	32
101,776	Mg-10Sc-12Y	13	44	40	51	7.6	28	29	29	29	28
				Mg-Sc Alloys From Prior Work							
100,639	Mg-10Sc-5Li	2	29	33	37	6.0	46	49	--	--	34
100,897	Mg-20Sc-6Ag	3	62	65	66	7.4	46	51	56	45	45
100,898	Mg-20Sc-10Cd	5	58	58	66	7.4	42	44	46	45	43
100,938	Mg-10Sc-8Y	16	42	42	50	8.6	25	27	26	26	--

*Strength as 10^3psi, modulus (E) as 10^6psi

F = As extruded

T4 = Heat treated at 950F for 1/2 hour, quenched

T6 = T4 plus 24 hour age at indicated temperature

FIG. 1 EFFECT OF AGING ON THE HARDNESS OF Mg-30 Sc EXTRUSIONS

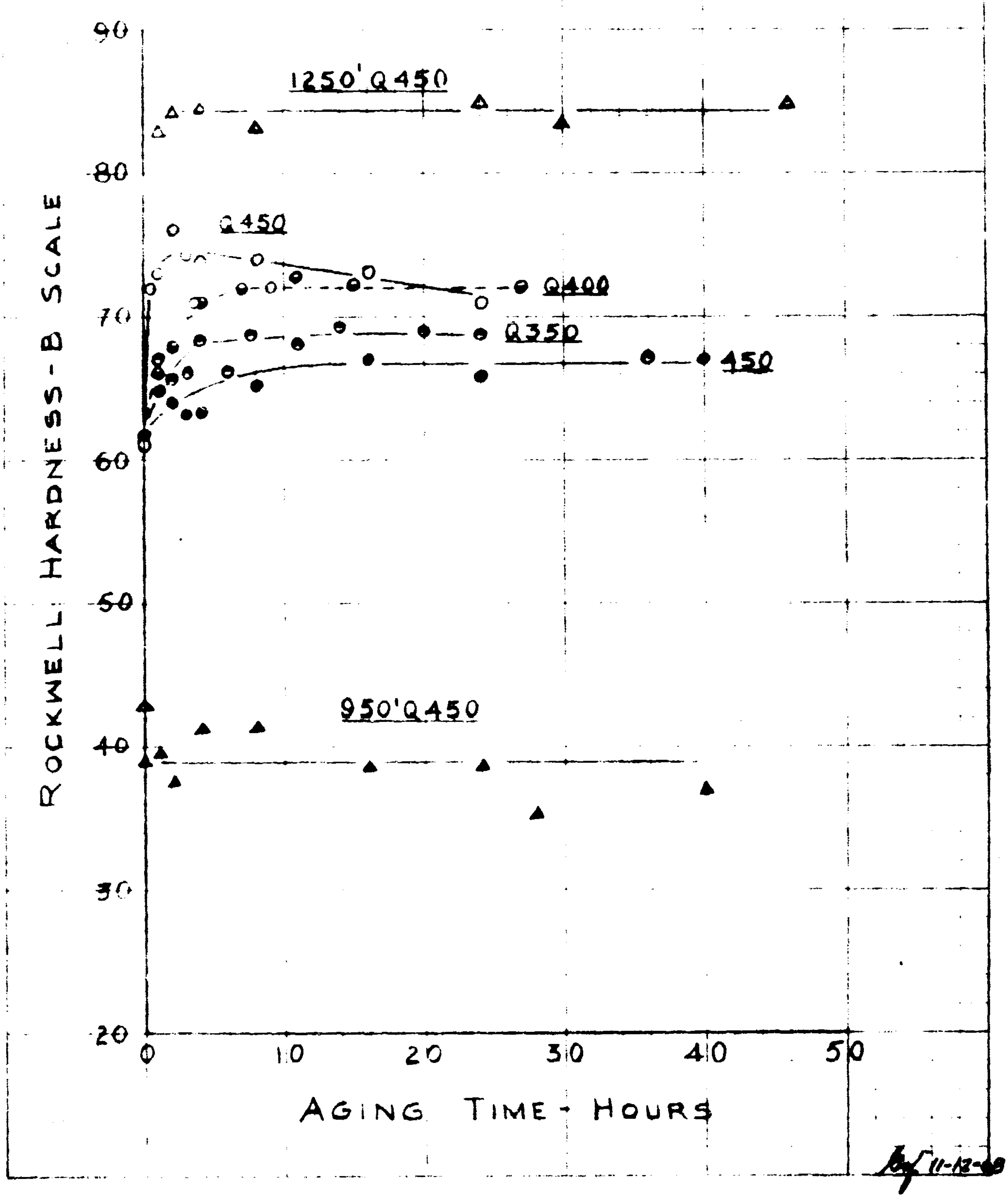
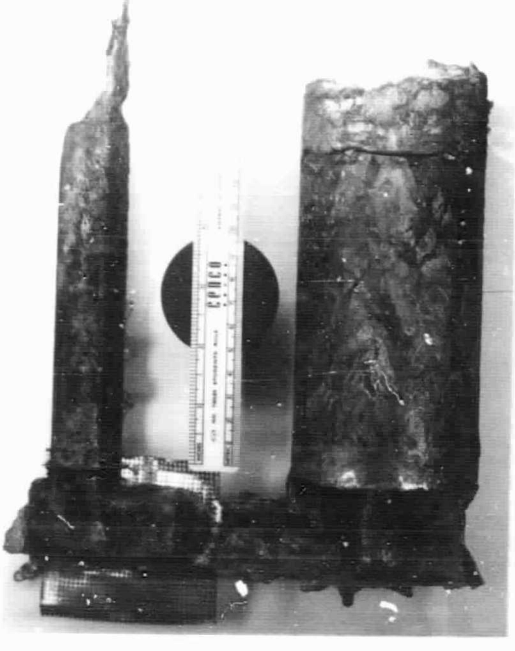


FIGURE 2

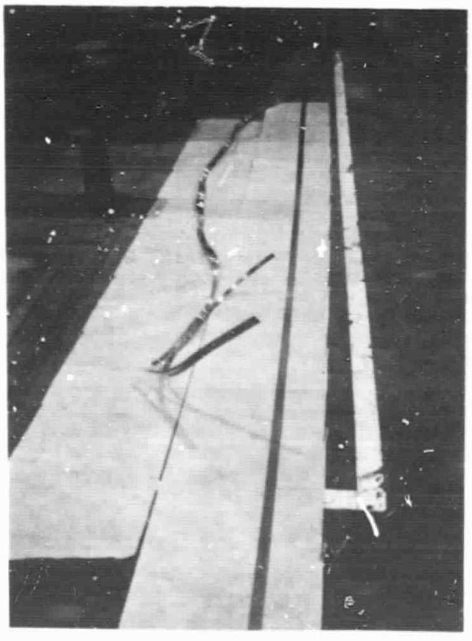
Mg-30Sc Casting and Extrusion

Alloy No. 101,805



3" Diameter Billet

Negative No. 65042



1/16" X 1 1/4" Extruded Strip

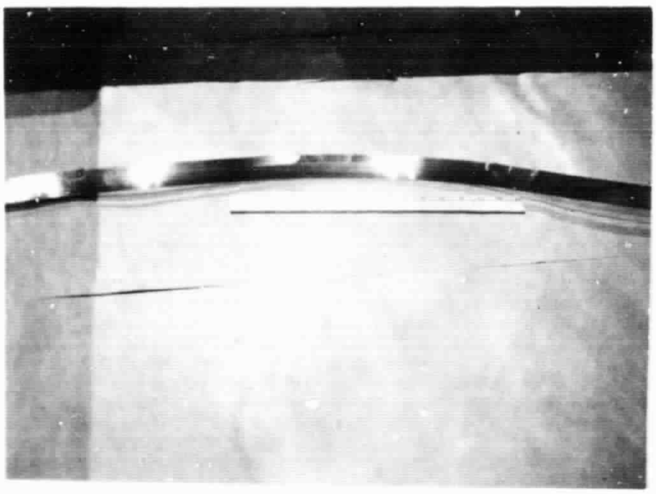
Quenched Part at Left

Negative No. 65163

FIGURE 3

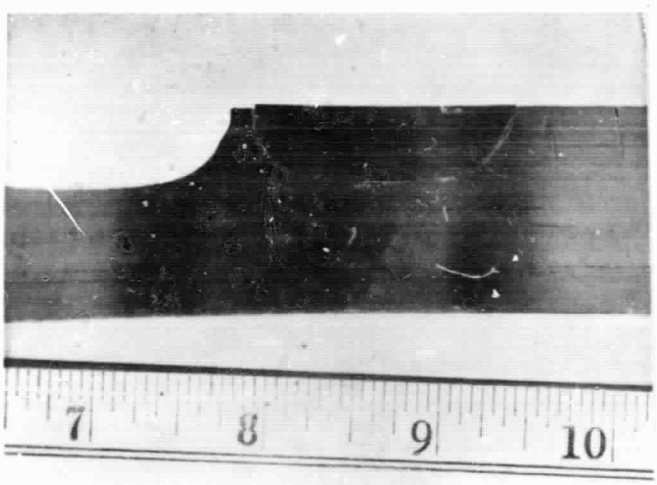
Mg-30Sc Extruded Strip (1/16" X 1 1/4")

Alloy No. 101,805



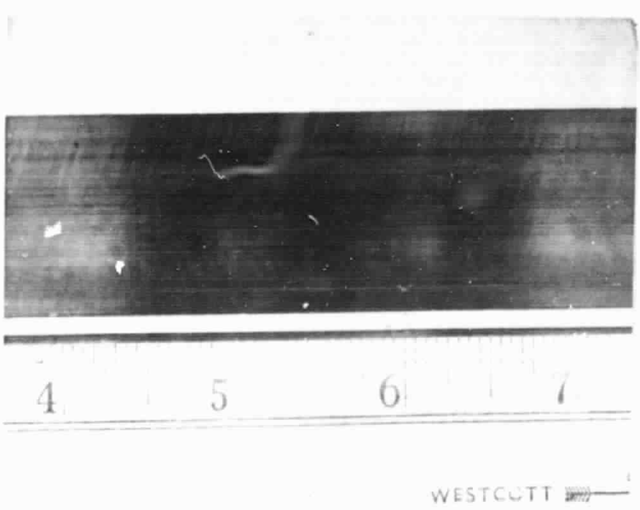
Quenched

Negative No. 65159



Quenched

Negative No. 65161



Not Quenched

Negative No. 65162