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REPORT R-1835

STRENGTH AND DUCTILITY OF 7000 SERIES WROUGHT ALUMINUM ALLOYS AS AFFECTED BY INGOT STRUCTURE

by

HARRY W. ANTES

February 1967

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FRANKFORD ARSENAL
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AMCMS Code 5025.11.29401.01.1
DA Project 1C024401A328

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Philadelphia, Pa. 19137

February 1967

ABSTRACT

A study was made of the effect of ingot structure on the strength and ductility of high strength wrought aluminum alloys. It was found that a fine cast structure facilitated complete homogenization which, in turn, resulted in significant increases in ductility and strength. A completely homogenized 7075-T6 alloy developed tensile properties of 85,000 psi ultimate tensile strength, 75,000 psi yield strength, with 40 percent reduction in area. Completely homogenized 7001-T6 alloy tensile properties were 102,000 psi ultimate tensile strength, 99,000 psi yield strength, with 19 percent reduction in area.

A method was devised for making small ingots having secondary dendrite arm spacing of less than 10 microns. This method involved multiple pass arc melting of commercial rolled plate with a tungsten electrode. This material could be completely homogenized after 3 hours at 900° F; homogenization of the original plate material was not complete after 120 hours at 900° F. Degree of homogeneity was determined by use of metallographic and electron microprobe analyses. The electron microprobe study also showed the preferential segregation of solutes in the microstructure.

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INTRODUCTION

High strength aluminum alloys, such as those of the 7000 series, usually freeze by the formation and growth of dendrites. The dendrite arm spacing (DAS) depends on the rate of solidification.[1*] Commercial ingots are usually direct chill-cast to promote more rapid solidification but, due to the large mass of the ingot, localized solidification times are long and a large DAS results. During solidification, solute elements are rejected by the solid as it forms, causing enrichment of the liquid and, ultimately, solute-rich interdendritic regions.

In order to attain a homogeneous ingot, the segregated solutes must diffuse across the dendrite arms. The larger the DAS, the longer the time for complete homogenization. In the case of commercial ingots, the DAS is so large that the time for complete homogenization is prohibitively long and, therefore, inhomogeneities are always present. These inhomogeneities are carried over to the wrought form during processing, resulting in an impairment of strength and ductility. Further, the mechanical fibering of these inhomogeneities during working results in mechanical property anisotropy.

If complete homogenization could be attained, then higher ductility could be expected. The realization of higher ductility at current strength levels would be desirable; however, it might be possible to sacrifice some of this ductility by adding more solute elements, thus producing even higher strength alloys than are currently available.

Further, if complete homogenization leads to more efficient utilization of solute elements, then more dilute alloys should have modestly high strengths with very high ductility. In all cases, it would be expected that the degree of mechanical property anisotropy due to mechanical fibering would be reduced. Therefore, it was the purpose of this investigation to produce cast structures that would facilitate homogenization, and to determine the effect of homogenization on the properties of high strength wrought aluminum alloys.

MATERIAL CLASSIFICATION

Commercial Alloys

In order to illustrate the nonhomogeneous condition that exists in commercial high strength wrought aluminum alloys, typical microstructures of 7001, 7075, and 7178 are shown in Figure 1. The chemical compositional specifications of these alloys are given in Table I.

*See REFERENCES.

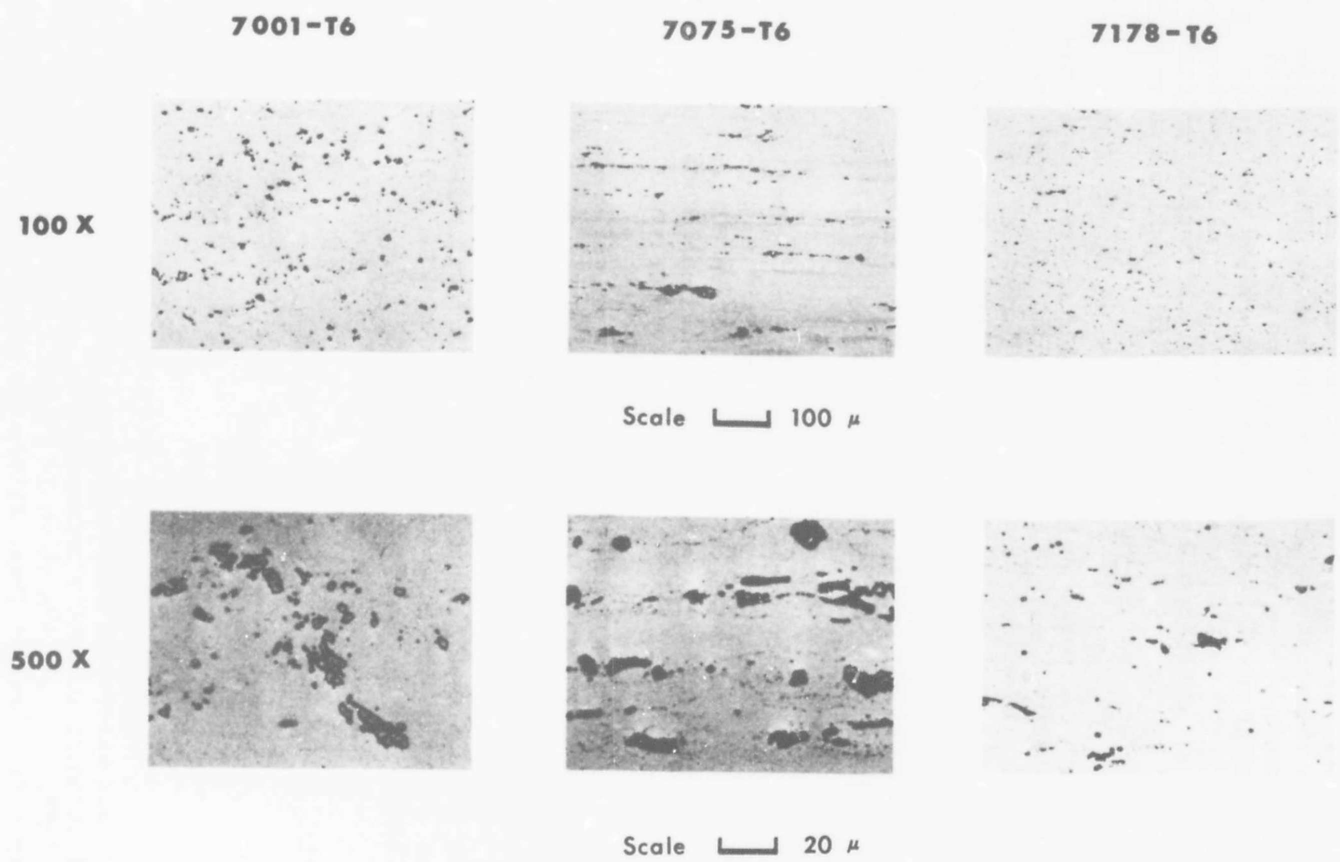


Figure 1. Microstructures of Commercial High Strength Wrought Aluminum Alloys

TABLE I.
Chemical Composition Limits of 7001, 7075, and 7178 Alloys

Element	% Element (by weight) in 7001	7075	7178
Zn	6.8 to 8.0	5.1 to 6.1	6.3 to 7.3
Mg	2.6 to 3.4	2.1 to 2.9	2.4 to 3.1
Cu	1.6 to 2.6	1.2 to 2.0	1.6 to 2.4
Cr	0.18 to 0.40	0.18 to 0.40	0.18 to 0.40
Si (max)	0.35	0.50	0.50
Fe (max)	0.40	0.70	0.70
Mn (max)	0.2	0.3	0.3
Ti (max)	0.2	0.2	0.2

It can be seen in Figure 1 that a considerable amount of undissolved second-phase material is present in each of these alloys. The solute elements associated with the undissolved phases were identified by electron microanalyses. Back-scattered electron images and characteristic X-ray images of the three commercial alloys are shown in Figures 2, 3, and 4. These data indicate that the second phases are regions of high copper and high iron-copper concentrations.

The second-phase material also was analyzed for magnesium, zinc, manganese, chromium, and silicon, but no significant enrichment above that of the matrix was found. Therefore, the problem of homogenization resolved itself into one of dissolving the copper-rich and the iron-copper-rich second phases. In order to accomplish this objective, two approaches were made. The first was to reduce the iron as low as possible, since this element has a maximum solid solubility of 0.03 percent in aluminum. The second was to produce cast structures with finer DAS to facilitate dissolving the second phase.

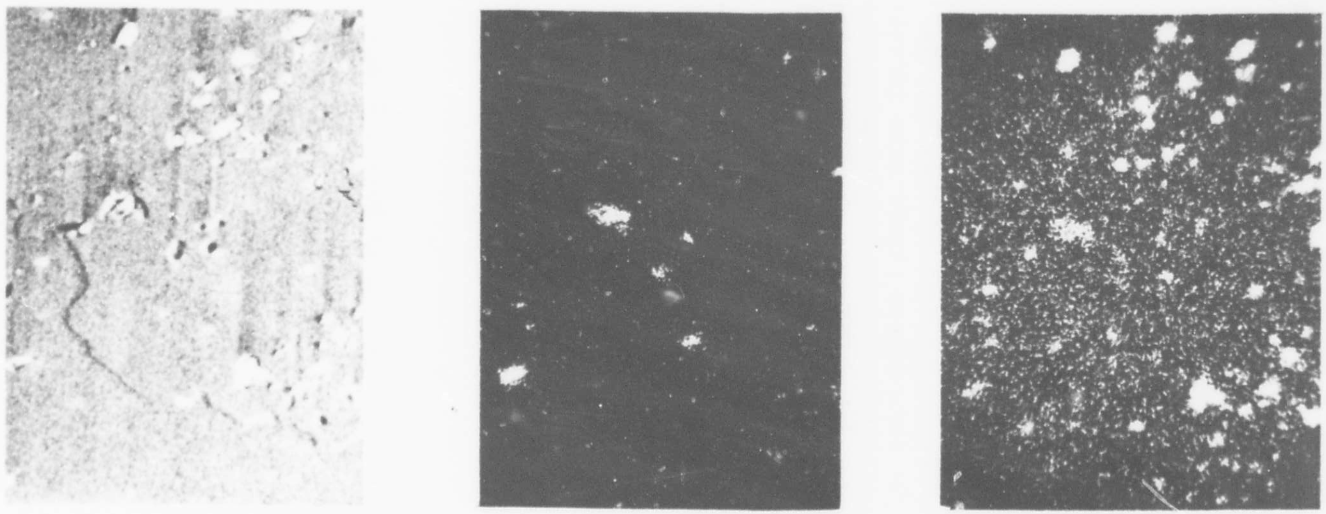
Commercially Produced High Purity Alloys

A special high purity 2000-lb ingot of 7075 alloy was made by a commercial producer. This alloy contained the following weight percentages of solutes: 5.63 Zn, 2.48 Mg, 1.4 Cu, and 0.21 Cr. All other elements combined were less than 0.02 percent by weight, including iron and silicon at less than 0.01 percent each. The ingot was cast and processed into rolled plate, using standard commercial techniques.

Microstructures of standard commercial 7075 and the special high purity 7075 are shown in Figure 5. It can be seen from this figure that the high purity alloy has less undissolved second-phase material, but a significant amount was still present. The second phase in the high purity material did not contain iron, but it was found to be

7001 – T6

Electron Image | **X-ray Fe(K_α)** | **X-ray Cu(K_α)**



Scale ⌴ **20 μ**

Mag: 500X

Figure 2. Electron Image, plus Iron and Copper X-ray Images, of Commercial 7001 Alloy Plate

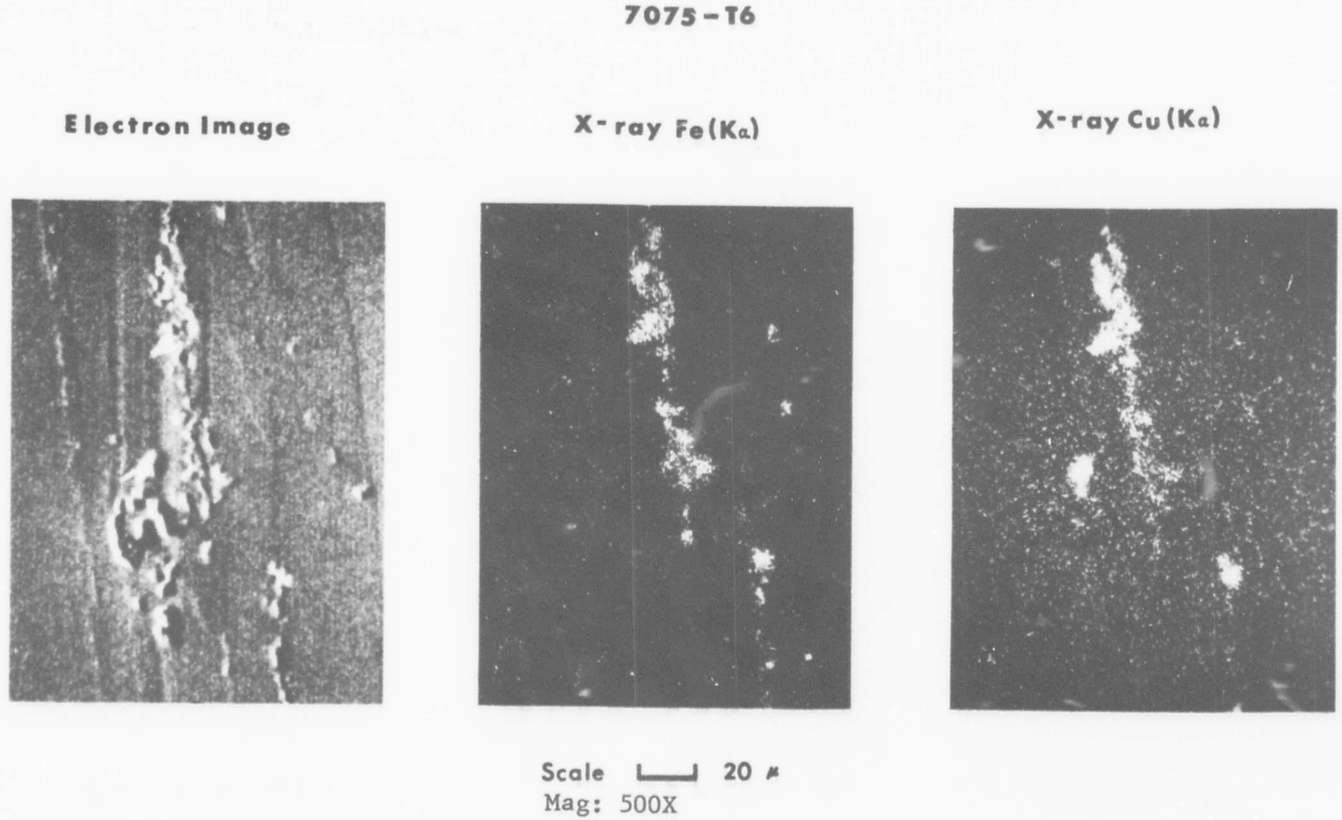


Figure 3. Electron Image, plus Iron and Copper X-ray Images, of Commercial 7075 Alloy Plate

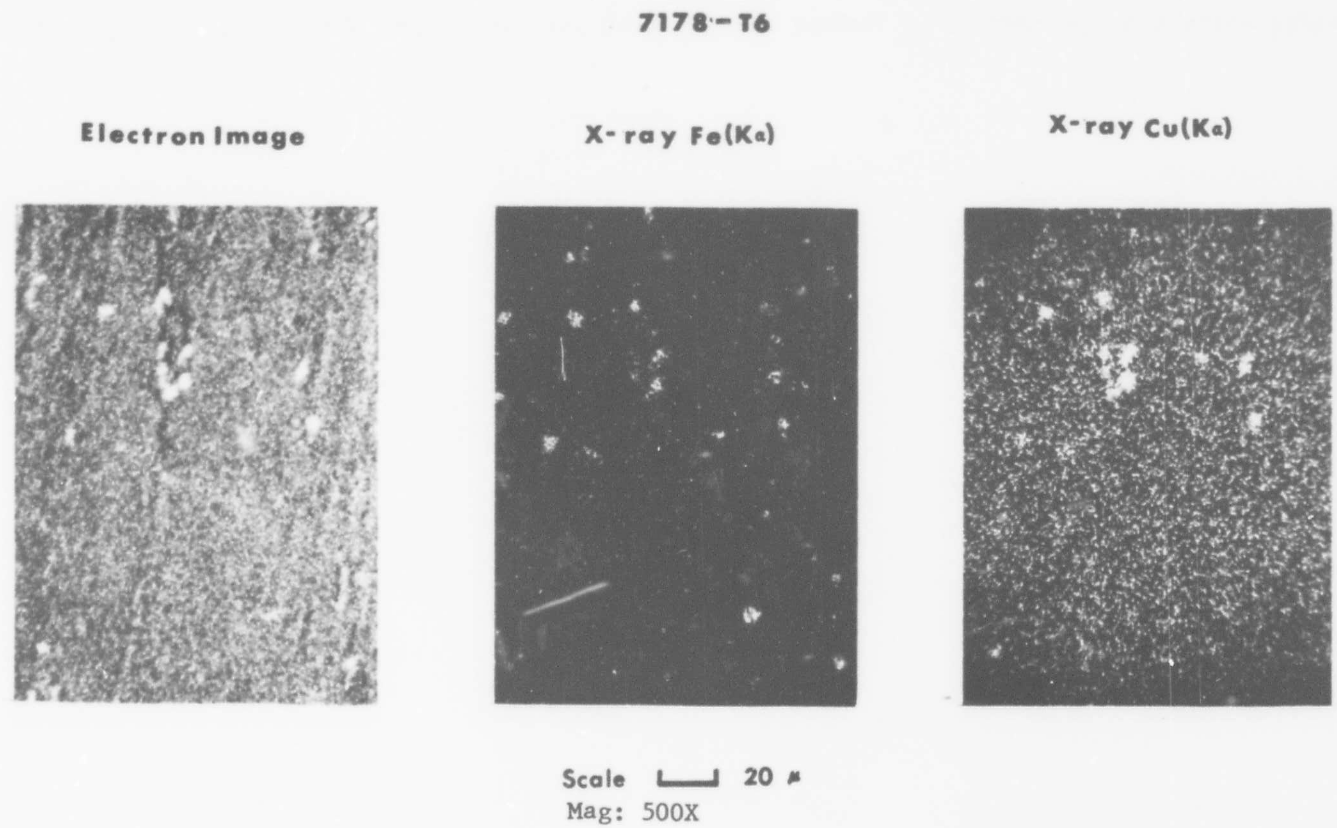


Figure 4. Electron Image, plus Iron and Copper X-ray Images, of Commercial 7178 Alloy Plate

Commercial 7075-T6

High Purity 7075-T6

Scale ⌴ **100 μ**

Mag: 100X

Figure 5. Typical Microstructures of Commercially Produced Standard and High Purity 7075-T6 Alloy Plate

enriched with copper. The slight effects of the increased purity and decrease in amount of second phase on the tensile properties are illustrated by the data in Table II.

TABLE II.
Tensile Properties of
Commercial and High Purity Commercial 7075-T6 Alloys
(Rolled Plate, 1-1/2 in. Thick)[2]

Specimen Orientation	Alloy[a]	Strength (ksi) Yield (0.2%)	Strength (ksi) Ultimate Tensile	Percent Elongation (7/16 gage)	Percent Reduction in Area
Longitudinal	C	84	90	10	13
Longitudinal	HP-C	82	89	11	15
Transverse	C	77	85	9	15
Transverse	HP-C	77	87	12	22
Short transverse	C	69	80	4	6
Short transverse	HP-C	67	76	2	6

[a] C - Commercial
HP-C - High Purity Commercial

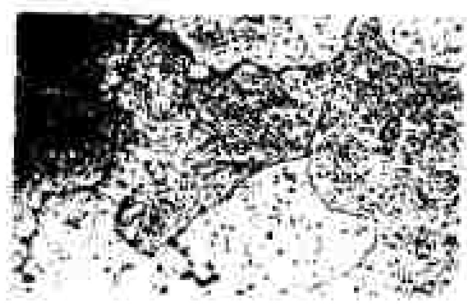
Tensile specimens used in this program were 0.140 inch diameter rounds with a 7/16 inch gage length. The data in Table II indicate that the high purity material has slightly higher ductility than the commercial material. Thus, reducing impurities to a very low level appears to have only a marginal effect on tensile properties of commercial 7075 alloy and no significant beneficial effect on the short transverse ductility.

Small Chill-cast Plates

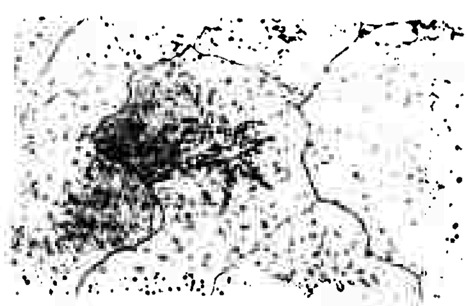
In order to produce structures with a finer DAS than the commercial ingots, a graphite mold with a copper end chill was used to chill-cast 1/2 by 3 by 6 inch plates of 7075 and 7001 alloys. The DAS was found to be about 40 to 50 microns for the chill-cast plates. A straight line-intercept lineal analysis technique was used to determine the DAS.

Typical as-cast structure and the structures after solutionizing for 6 and 24 hours are shown in Figure 6. It can be seen from this figure that after a 6-hour homogenization treatment at 900° F, a substantial amount of second-phase material remained in the interdendritic regions and at grain boundaries. Increasing the solutionizing time to 24 hours reduced the amount of second-phase material, but a significant amount still remained.

As-Cast



Solution Treated for 6 Hours



Scale ⌴ 100 μ
Mag: 100X

Solution Treated for 24 Hours

Figure 6. Effect of Solutionizing at 900° F on the Structure of 1/2 inch thick Chill-cast Plates of 7075 Alloy

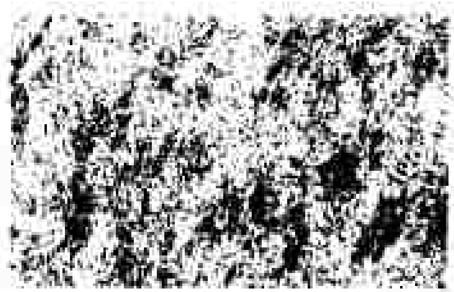
The chill-cast plates homogenized 24 hours at 900° F were forged to 3/8 inch diameter bar. The as-forged structure and the structures produced by re-solutionizing 7075 at 900° F for 2 and 100 hours are shown in Figure 7. A standard single-step aging (24 to 28 hours at 250° F) was used for the T6 treatment.

The effect of increasing solutionizing time (increased homogeneity) on the tensile properties of chill-cast and forged 7075-T6 and T001-T6 is shown in Figure 8. The bar graphs in this figure represent the properties of commercial alloys for the T6 condition; the curves represent the properties of chill-cast and forged material. In the case of the 7075-T6 material (Figure 8a), the strength of the chill-cast and forged material remained essentially constant with increasing solutionizing time - at about the same level as commercial material. The ductility also remained constant as the solutionizing time was increased, but the levels of the elongation and reduction in area were considerably higher than the commercial material. These data indicate that a relatively high degree of homogenization was attained in the chill-cast and forged material, even for the shortest solutionizing times.

The tensile data for the chill-cast 7001 material are presented in Figure 8b. It can be seen from these data that the strength of the chill-cast material was slightly lower and the ductility slightly higher than that of commercial material when both materials were solutionized for 5 hours at 900° F and then aged. A considerable increase in ductility, with less significant changes in strength, was observed for the chill-cast and forged 7001 material when the solutionizing time was increased.

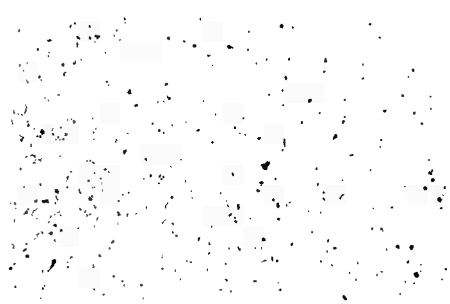
The difference in response to solutionizing of the chill-cast and forged 7075 and 7001 alloys may be related to a difference in copper and iron contents and differences in total amount of solutes. If it is assumed that an increase in ductility without significant change in strength is the result of an increase in homogeneity (i.e., a decrease in the amount of second-phase material), then it would take a longer time to homogenize a higher solute alloy such as 7001 since it originally contains a greater amount of interdendritic second-phase material.

It is interesting to note that for both 7075 and 7001 alloys, special chill-casting and homogenization treatments resulted in reduction-in-area (RA) values of approximately 40 and 30 percent, representing values about double that of commercial alloys. Although increased ductility was achieved through increasing homogeneity, not all second-phase material was eliminated and, therefore, mechanical property anisotropy probably would exist to some degree.



As-Forged

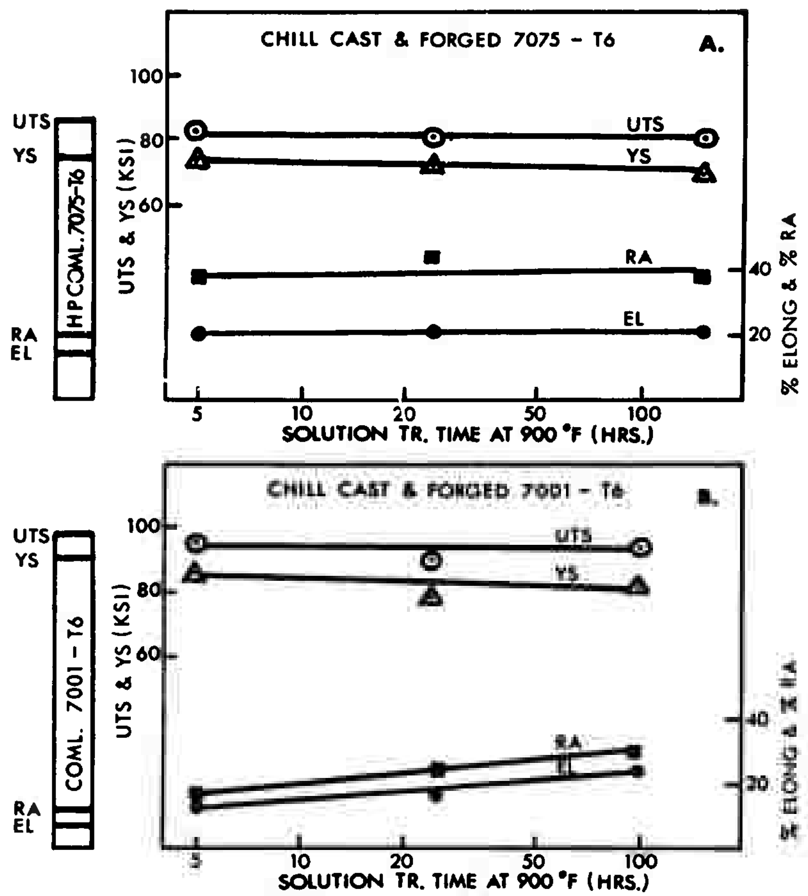
Solution Treated for 2 Hours



Scale 100 μ
Mag: 100X

Solution Treated for 100 Hours

Figure 7. Effect of Solutionizing at 900° F on the Structure of Forged Chill-cast Plates of 7075 Alloy



Bar-graphs at left are tensile properties of commercial alloys, solution treated for 5 hours at 900 F and aged 24 hours at 250 F

Figure 8. Effect of Solution Treatment Time on the Tensile Properties of Chill-cast and Forged 7075-T6 and 7001-T6 Alloys

Specially Cast Fine Dendrite Material

In order to facilitate complete homogenization, it was necessary to produce cast structures with a DAS less than the 40 to 50 microns achieved in the 1/2 inch thick chill-cast plates. Casting with a DAS of from 5 to 10 microns were made by chill-casting 1/8 inch diameter rods in an aluminum mold. A heat treatment of 900° F for three hours produced a high degree of homogeneity in the 1/8 inch diameter cast high purity 7075 material. By comparison, the commercially produced high purity 7075 had a considerable amount of second-phase present after a treatment of 120 hours at 900° F. The microstructures of both materials before and after thermal treatment are shown in Figure 9.

In order to determine the wrought properties of the fine dendrite material, the rods were solution-treated, quenched, and then cold-swaged down to 0.06 inch diameter rods. The swaged rods were re-solution treated, quenched, and aged. The tensile properties are shown for the commercial, high purity commercial, and specially cast swaged rods in Table III.

TABLE III.
Tensile Properties of Commercial,
High Purity Commercial, and Specially Cast 7075 Alloy

7075-T6 Material	Strength (ksi) Ultimate Tensile	Strength (ksi) Yield (0.2%)	Percent Reduction in Area
Commercial	85	75	15 to 18
High purity commercial	85	75	20 to 25
Specially cast fine dendrite	85	75	40 to 45

These alloys were solution-treated for four hours at 900° F, quenched in water, and aged for 24 hours at 250° F. It can be seen from the data in Table III that the highly homogeneous specially cast fine dendrite material exhibited considerably higher reduction-in-area values than either the standard commercial or the high purity commercial alloys.

In view of the high degree of homogeneity achieved with the specially cast fine dendrite 7075 alloy and the resulting high ductility, additonal specially cast rods were made of 7001 alloy. It was found that even with this higher solute material, the fine dendritic structure facilitated homogenization. Virtually complete homogenization was achieved within three hours at 900° F. The as-cast and homogenized structures are shown in Figure 10. Attempts were made to cold-swage the homogenized 7001 specially cast fine dendrite material; however, the alloy cracked, indicating that higher solute alloys such as 7001 must be worked warm or hot.

Weld Casting

A weld-casting technique was developed to make a larger mass with the desired fine DAS. The technique consisted of striking a direct current arc between a nonconsumable tungsten electrode and an aluminum alloy plate. The electrode was moved at a controlled velocity along the plate. The metal, melted by the arc, froze rapidly due to rapid chilling by this arrangement. A schematic of the weld-casting technique is shown in Figure 11. Small ingots of 7001, approximately 1/2 by 1/2 by 10 inches, were made using this technique. The DAS of these ingots was found to be in the range of 5 to 20 microns, depending on the power input to the arc and electrode velocity.

The electron image of a typical weld casting is shown in Figure 12. Also in this figure are X-ray images showing the distribution of solute elements in the as-cast condition and after homogenization. It can be seen from this figure that in the weld-cast material, copper was preferentially segregated at the interdendritic or cell wall regions. Zinc was more uniformly distributed, with a slight increase in concentration at the cell walls. Magnesium was uniformly distributed throughout the alloy. A homogenization treatment of three hours at 900° F, followed by water quenching, completely removed all traces of cell walls and uniformly distributed all the solute elements, producing a high degree of homogeneity in the material.

A 7001 weld-cast ingot was cut away from the base plate with a band saw. This ingot was hot rolled at 900° F from 1/2 inch diameter down to 1/4 inch square bar stock in grooved rolls. This material was solution-treated for four hours at 900° F, water quenced, and aged at 250° F.

A plot of hardness vs aging time is shown in Figure 13a. This curve shows that relatively high hardness exists over the range of aging times from 24 to 98 hours. The tensile properties within this range are shown in Figure 13b. These curves show that yield strength, ultimate strength, and reduction in area increase with increasing aging time up to 98 hours. A comparison may be made between the tensile properties of commercial 7001 alloy and weld-cast 7001 alloy from the data in Table IV.

It can be seen from the data in Table IV that the weld-cast material has both higher strength and ductility than the commercial material. These increases may be attributed to the higher degree of homogeneity achieved in the weld-cast material.

The high strengths and ductilities realized by a high degree of homogenization of fine dendrite spaced material are attractive. However, for metal forming processes and certain military applications, higher ductility, even with somewhat lower strengths, would be more

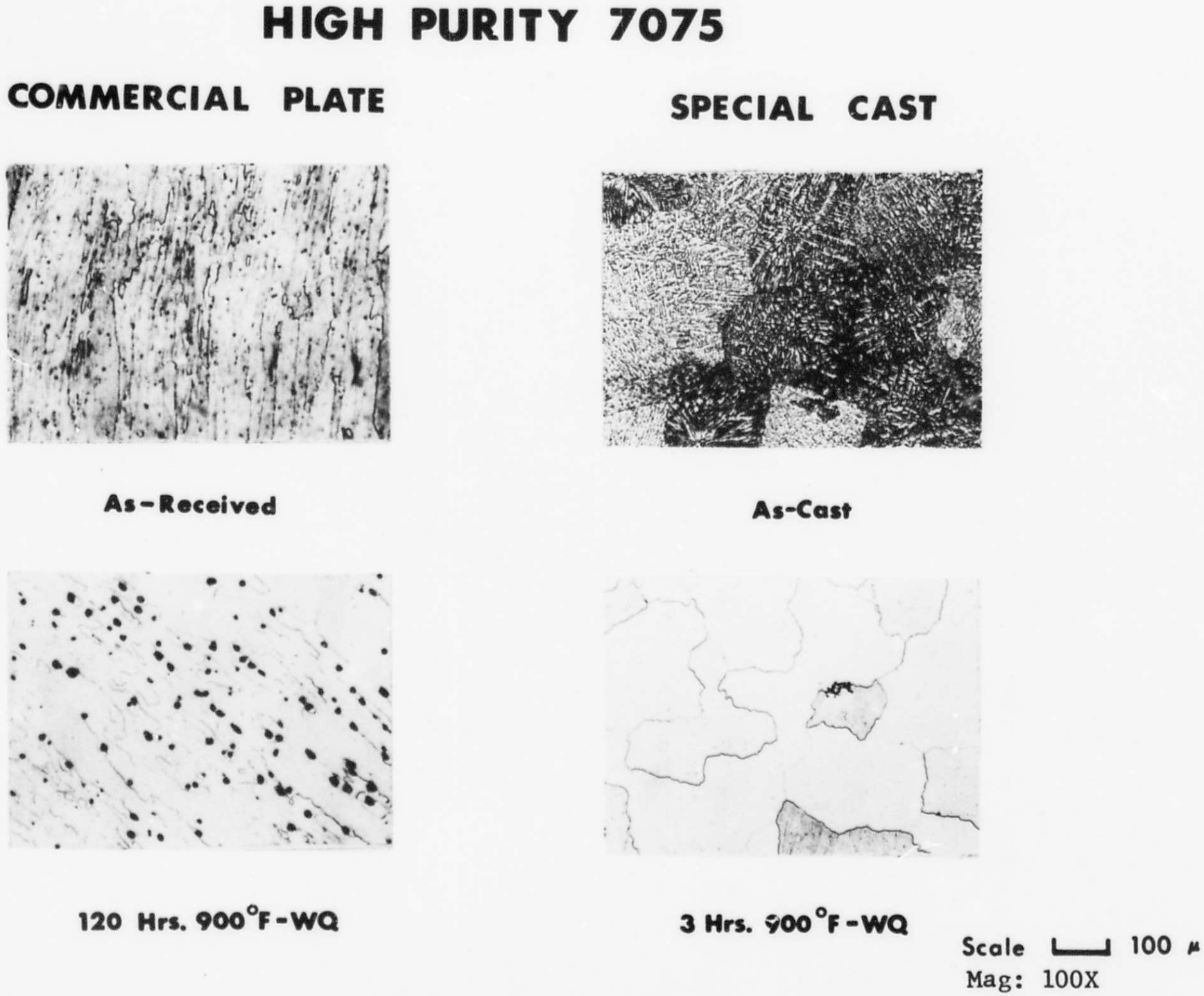


Figure 9. Effect of Homogenizing Treatments on Commercially Produced and Specially Cast High Purity 7075 Alloy

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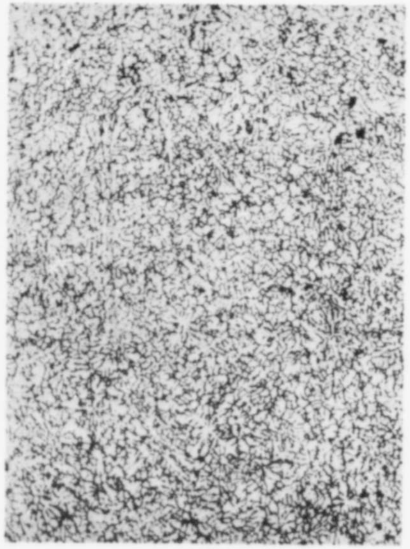

As-Cast
100X
100 μ

As-Cast
500X
20 μ

Homogenized
3 hrs 900°F
100X
100 μ

Figure 10. Microstructures of Cast and Homogenized 1/8 inch diameter Chill-cast 7001 Rod

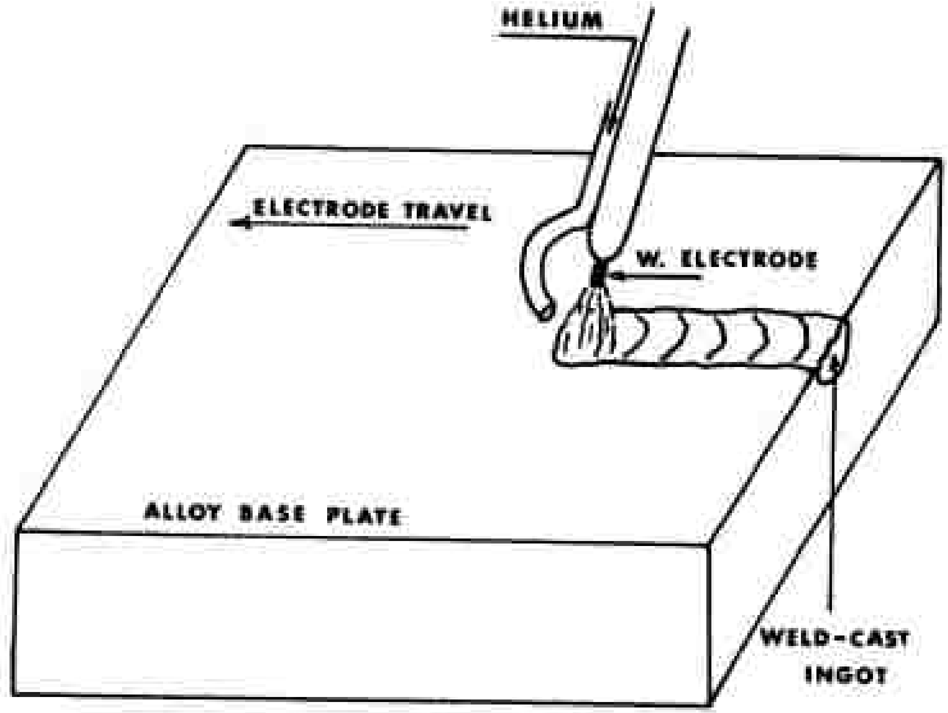

Figure 11. Schematic of Weld-casting Apparatus

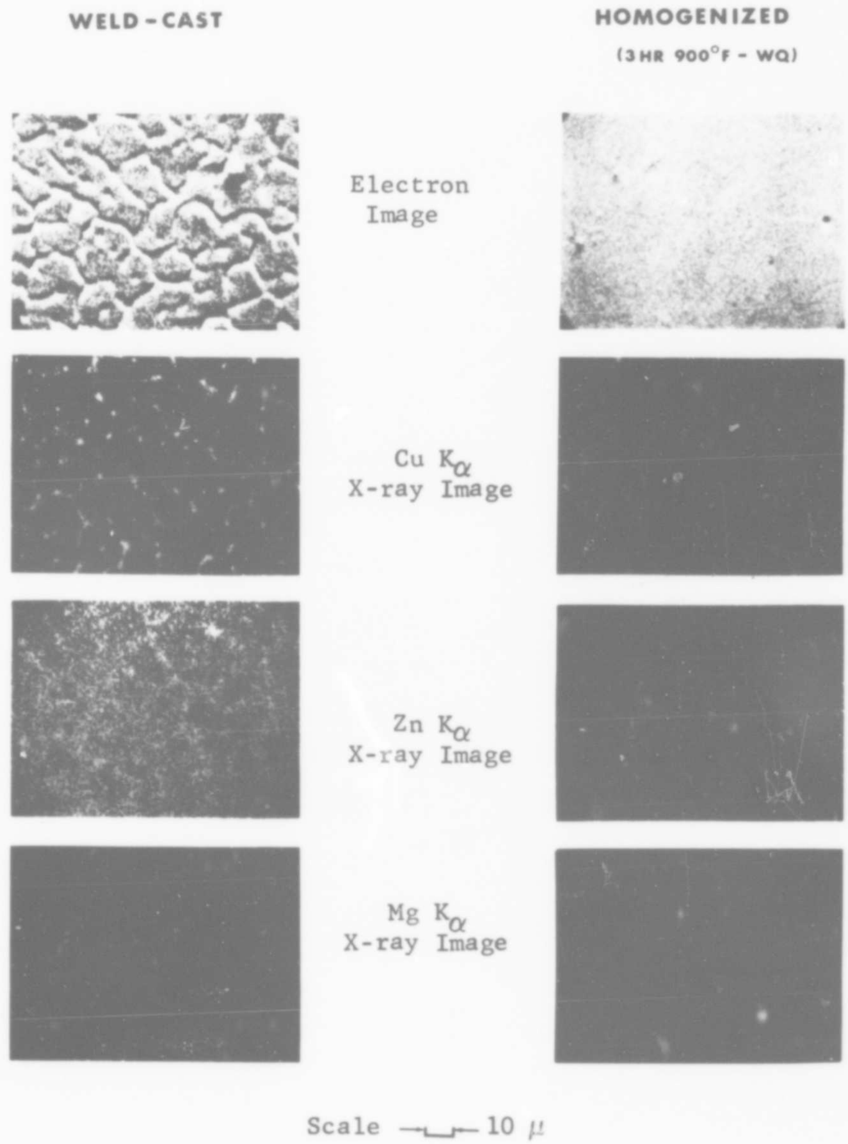

Figure 12. Electron Images, plus Copper, Zinc, and Magnesium X-ray Images, of Weld-cast and Homogenized 7001 Alloy

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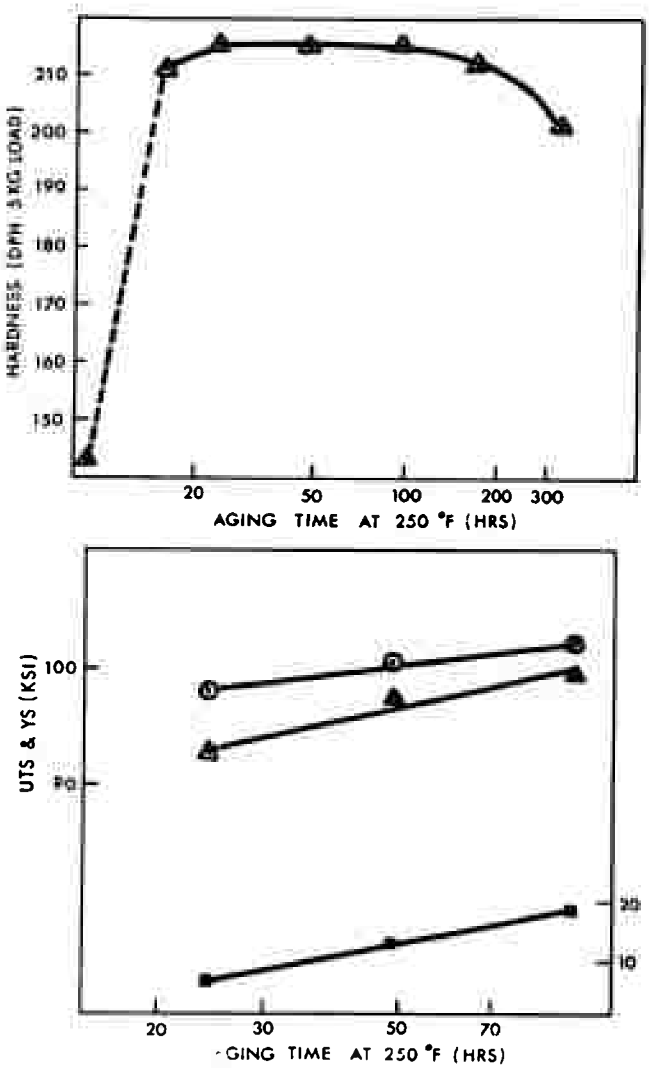


Figure 13. Effect of Aging at 250° F on Hardness and Tensile Properties of a Weld-cast and Hot rolled 7001 Alloy

TABLE IV.
Chemical Composition and Tensile Properties of
Commercial and Weld-cast 7001-T6 Alloys

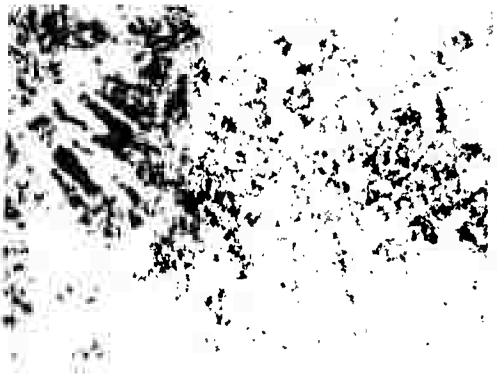
	Commercial Alloy	Weld-cast Alloy
Composition (weight percent)		
Zn	7.40	7.90
Mg	3.00	2.70
Cu	2.10	1.60
Cr	0.25	0.16
Tensile properties		
Ultimate tensile strength (ksi)	98.0	102.3
Yield strength (ksi)	91.0	99.4
Reduction in area (%)	12	19

desirable. Therefore, a leaner solute alloy was made for evaluation. This alloy contained 4.58 Zn, 2.14 Mg, 1.56 Cu, and 0.18 Cr, with the balance being aluminum. This material was made in weld-cast form, homogenized for three hours and forged to 1/4 inch round bar stock. It was found that on re-solution treatment of the forged material, complete homogenization could be achieved by a 10-minute solutionizing time at 900° F.

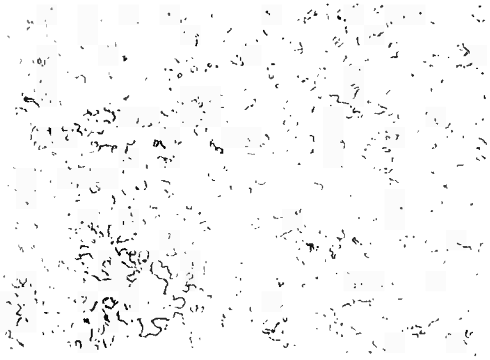
The microstructures of the as-forged material and the 10-minute solutionized material are shown in Figure 14. These data indicate that a high degree of homogeneity was maintained during the forging operation. The forged material was re-solutionized for three hours at 900° F for aging studies. The effect of aging time at 250° F on the hardness and tensile properties of this alloy is shown in Figure 15. It can be seen from this figure that hardness, yield strength, and ultimate strength increased over the aging range studied (8 to 135 hours), with highest strengths observed being 65,000 psi yield strength and 75,000 psi ultimate tensile strength. These strengths were accompanied by a reduction in area of 51 percent.

DISCUSSION

The beneficial effects of increased degree of homogeneity on the tensile properties of sand cast aluminum-copper alloys were demonstrated by Passmore, Flemings, and Taylor.[3] These investigators obtained significant increases in strength and ductility through high temperature-long time solutionizing treatments, although in most cases these materials were still not completely homogeneous. Complete homogenization



AS-FORGED



SOL. TR. 10 MIN. 900 °F

Scale 100 µ
Mag: 100X

Figure 14. Microstructures of an As-forged and a 10-minute Solutionized Weld-cast "Leaner Solute" Alloy

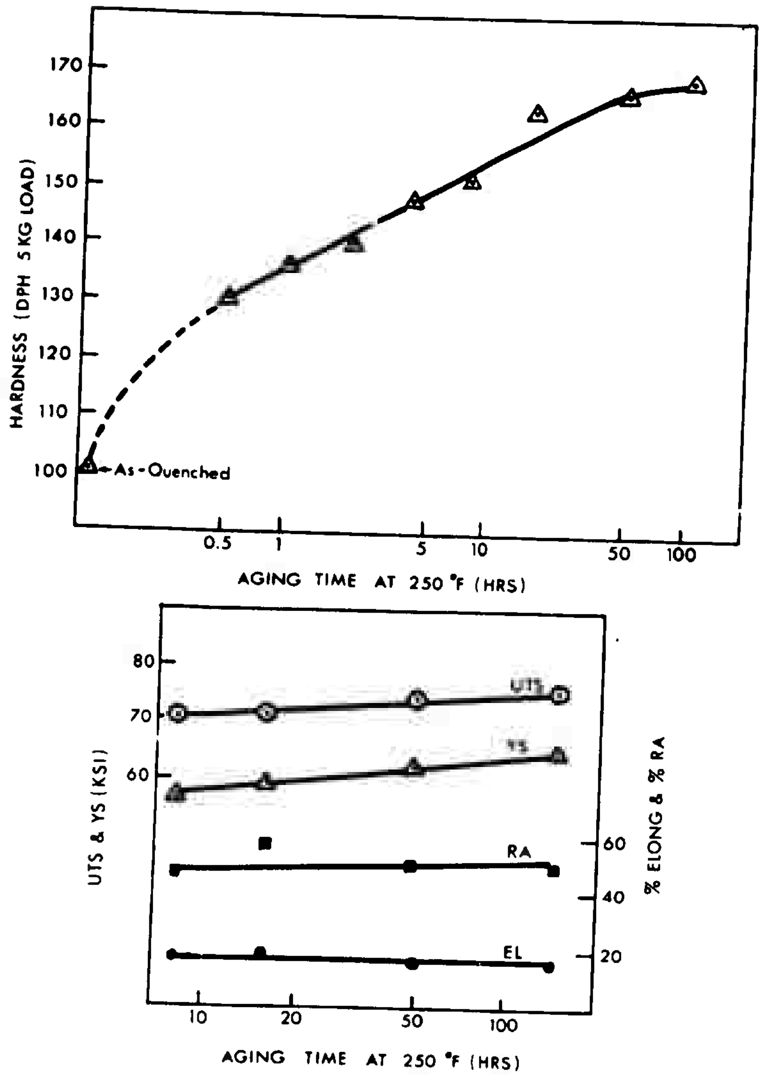


Figure 15. Effect of Aging at 250° F on Hardness and Tensile Properties of a "Leaner Solute" Alloy

was achieved only in those sections of the castings that were very close to a chill (fine DAS material).

In the case of commercial high strength wrought aluminum alloys, there are two principal factors which preclude complete homogenization. The first is the relatively coarse cast structure of the primary ingot; the second is the fact that iron is present in these alloys as an impurity. The effects of the coarse structure have been discussed. The presence of iron in undissolved second phases is clearly evidenced by Figures 2, 3, and 4.

According to Phillips,[4] in Al-Cu-Fe equilibrium, a beta phase exists which encompasses the composition Cu_2FeAl_7. The presence of this phase has been observed in aluminum alloys containing copper and the impurity, iron.[4,5] It was observed by Flemings et al[5] and during homogenization studies in this work, that iron-rich compounds are virtually impossible to dissolve. Therefore, iron content must be limited to a very low level if complete homogenization is to be achieved. The importance of a fine DAS in facilitating complete homogenization is exemplified by comparing the 50 μ DAS material in Figure 6 with the 5 to 10 μ DAS specially cast material in Figures 9 and 10.

It has been shown[6] that the relationship between the secondary dendrite arm spacing (d) and the local solidification time (θ_f) is given by

$$d = 7.5\ \theta_f^{0.39}$$

According to this equation, in order to obtain a DAS of 10 microns, the local solidification time should be on the order of two seconds. This short solidification time requires a high rate of heat extraction or good chilling. The best chilling condition is obtained when no interfacial resistance to heat flow exists between the freezing alloy and the chill. This condition is achieved during welding type operations. Brown and Adams[7] showed that MIG (metal inert gas) weld deposits of aluminum-copper alloys had a DAS of from 2 to 10 μ, depending on the welding conditions. On the basis of this work, the weld-casting technique was developed for producing 5 to 10 μ DAS material in larger sections than 1/8 inch diameter chill-cast rods.

The ability to homogenize completely a 7001 weld-cast alloy is illustrated by the electron and X-ray images in Figure 12. The microstructures of homogenized weld-cast 7001 alloy after hot rolling, resolution treating, aging for 48 and 98 hours, are shown in Figure 16. Electron microanalyses of these specimens revealed a uniform distribution of all solutes, indicating a high degree of homogenization. The mottling that appears within the grains is due to etch pits present at subboundaries.

Figure 17 is a higher magnification photomicrograph of the solution-treated material. Triangular etching pits are clearly visible in this

HOT ROLLED WELD-CAST 7001 ALLOY

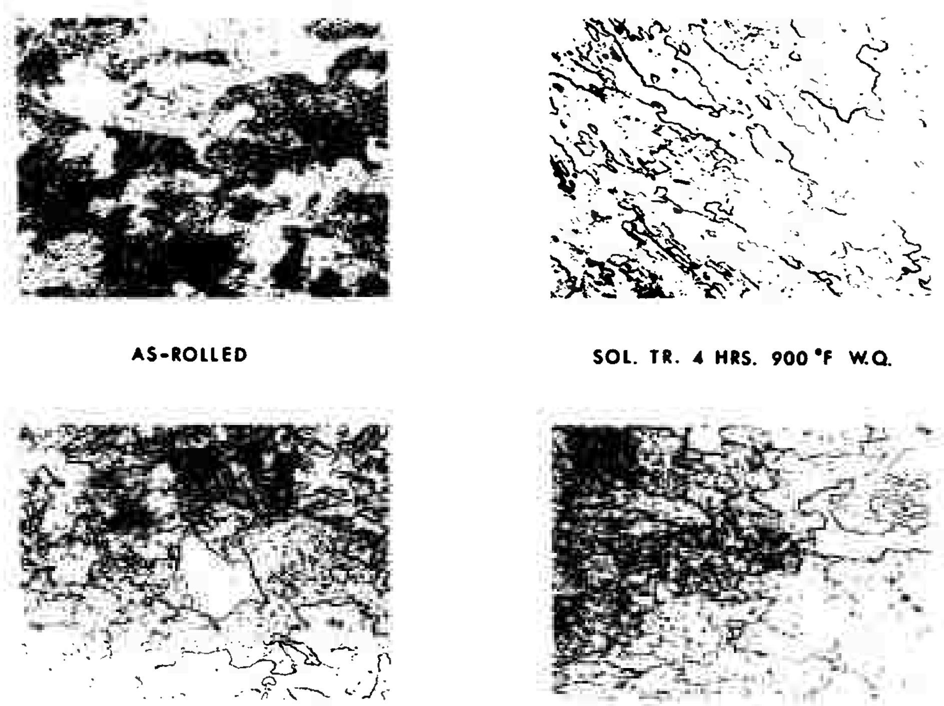
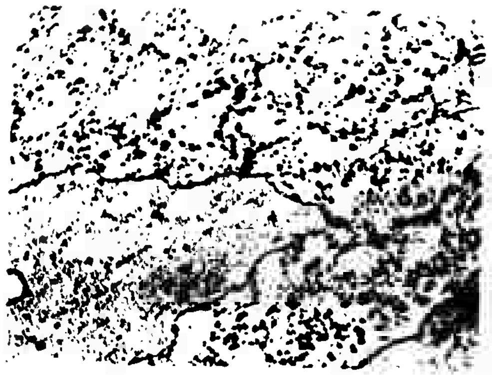


Figure 16. Microstructures of Weld-cast 7001 Alloy, Hot Rolled and Heat Treated



Scale ⊔ 10 μ
Mag: 1000X

Figure 17. Microstructure of Hot Rolled Weld-cast 7001 Alloy, Solution Treated at 900° F for Four Hours and Water Quenched

figure at the sub-boundaries. The presence of subgrains increases yield strength[8] since they act as barriers for dislocation pile-up. Subgrains have a lesser effect on ultimate strength and, usually, the presence of subgrains causes a slight decrease in ductility.

The data in Table IV illustrate increases in yield and ultimate strength for the weld-cast 7001 alloy over the commercial alloy, but with higher rather than lower percent reduction in area. This higher ductility is obviously the result of greater homogeneity of the weld-cast 7001 alloy.

As a result of this investigation, it has been shown that complete homogenization can be attained in 7000 series alloys and that high strength with high ductility is realized as a result of the homogeneity. Although this work was done with small laboratory castings, the results indicate the potential improvement of 7000 series alloys and imply that similar results may be expected in other alloys.

CONCLUSIONS

1. Complete homogenization results in a substantial increase in ductility of 7000 series alloys, with little or no degradation of strength and, in certain cases, strength may be increased concurrently with improved ductility.

2. The production of a fine-cast structure (i.e., $<15\ \mu$ dendrite arm or cell spacing) facilitates complete homogenization of 7000 series alloys.

3. Commercial high strength wrought aluminum alloys of the 7000 series contain undissolvable copper- and iron-copper-rich second phases.

4. Eliminating the impurity element (iron) does not in itself eliminate the problem of undissolved second phases, although iron-rich phases are virtually impossible to dissolve.

RECOMMENDATIONS

In view of the attractive properties that have been achieved by high degrees of homogenization of wrought aluminum alloys, it is recommended that studies be made to determine techniques for producing more massive forms of highly homogeneous wrought alloys.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) FRANKFORD ARSENAL, Philadelphia, Pa. 19137 (SMUFA L3300)	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP N/A

3 REPORT TITLE

STRENGTH AND DUCTILITY OF 7000 SERIES WROUGHT ALUMINUM ALLOYS AS AFFECTED BY INGOT STRUCTURE

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical research report

5 AUTHOR(S) (Last name, first name, initial)

ANTES, Harry W.

6 REPORT DATE February 1967	7a TOTAL NO OF PAGES 32	7b. NO OF REFS Eight
8a CONTRACT OR GRANT NO. AMCMS Code 5025.11.29401.01.1 b PROJECT NO DA Project 1C024401A328 c d	9a ORIGINATOR'S REPORT NUMBER(S) Frankford Arsenal Report R-1835 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10 AVAILABILITY/LIMITATION NOTICES

Distribution of this report is unlimited.

11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY AMCRD-RS-CM

13 ABSTRACT

A study was made of the effect of ingot structure on the strength and ductility of high strength wrought aluminum alloys. It was found that a fine cast structure facilitated complete homogenization which, in turn, resulted in significant increases in ductility and strength. A completely homogenized 7075-T6 alloy developed tensile properties of 85,000 psi ultimate tensile strength, 75,000 psi yield strength, with 40 percent reduction in area. Completely homogenized 7001-T6 alloy tensile properties were 102,000 psi ultimate tensile strength, 99,000 psi yield strength, with 19 percent reduction in area.

A method was devised for making small ingots having secondary dendrite arm spacing of less than 10 microns. This method involved multiple pass arc melting of commercial rolled plate with a tungsten electrode. This material could be completely homogenized after 3 hours at 900° F; homogenization of the original plate material was not complete after 120 hours at 900° F. Degree of homogeneity was determined by use of metallographic and electron microprobe analyses. The electron microprobe study also showed the preferential segregation of solutes in the microstructure.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Wrought Aluminum Alloys						
Casting						
Solidification						
Microsegregation						
Homogenization						
Electron Microchemical Analysis						
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