Some Effects of Yttrium on Ti-5522S Alloy Welds

Losses in toughness are apparently caused by a bead-like grain boundary phase that consists of pores and is not correspondent with any chemical segregation

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ABSTRACT. Some Ti-5Al-5Sn-2Mo-2Zr-0.25Si alloy sheet was found to contain 250 ppm yttrium which had been intentionally added by the alloy supplier. Bead-on-plate welds of this sheet were evaluated microstructurally as well as for strength and toughness. These data are compared to those obtained with the same alloy which was not doped with yttrium and also to results obtained with Ti-6Al-4V alloy.

The yttrium additions were deleterious to the mechanical properties of Ti-5Al-5Sn-2Mo-2Zr-0.25Si alloy welds. The presence of yttrium is shown to be accompanied by the formation of a bead-like grain boundary phase. This phase, which apparently causes the loss in toughness, is shown to be pores and not correspondent with any chemical segregation, including yttrium.

Introduction

In recent years, the addition of small amounts of silicon to high strength titanium alloys has resulted in improved physical properties; among the alloys that demonstrate such advantage is Ti-5Al-5Sn-2Mo-2Zr-0.25Si.[1] Because of its good combination of high temperature yield strength, ductility, and creep resistance, this alloy was chosen, through the offices of the Air Force Materials Laboratory, for further development. Since the alloy is certain to see considerably expanded use if its GTA weld joint efficiency is high, a cursory investigation of weldability was included.

Between the time Ti-5522S had been screened and the time it was chosen for further development, another fundamental titanium alloy investigation had reached fruition. Titanium alloy producers had found that small additions (100 to 2000 ppm) of yttrium, added as either Y or Y_2O_3, provoke considerable grain refinement in hot-worked Ti-6Al-4V (Ti-64) and also in Ti-3Al-8V-6Cr-4Mo-4Zr (Ti-38-6-44).[2] This refinement affords significant advantage through improvement in ultrasonic inspectability and is often accompanied by increased ductility with no significant loss of other mechanical properties. Yttrium additions are sometimes accompanied by loss of toughness, but judicious metallurgy can minimize this loss while retaining the attendant advantages.

Conventional GTA welds in high strength titanium alloys typically display low joint efficiency. Such low efficiencies are usually manifest as low ductility and low fracture toughness.[3,4] Simpson[5] has reported that, when Ti-6Al-6V-2Sn is GTA welded through use of a yttrium-doped filler metal and the resulting weldments are heat treated, the grain size of the weld becomes smaller with increasing concentrations of yttrium in the filler wire. The data, however, indicate catastrophic loss of ductility, fracture toughness, and fracture energy for filler metal yttrium levels which exceed approximately 200 ppm.

Due to the advantage that small concentrations of yttrium in titanium alloys offer to the alloy producer, the master heat of Ti-5Al-5Sn-2Mo-2Zr-0.25Si (Ti-5522S) which was furnished to the Air Force was intentially doped to 250 ppm Y. Previous scientific studies,[5] however, indicated that such additions could have serious deleterious effects on the properties of GTA welds in this alloy. The existence and extent of such effects was thus investigated for selected properties.

Procedure

The experimental procedure for evaluating the effects of yttrium in Ti-5522S was somewhat bound by the limited availability of non-yttriated material. Only three small pieces of Ti-5522S which contained no Y were available to the authors at the outset of the program. These pieces were alpha-beta processed to ⅛ in. (3 mm) thick sheet stock; each piece resulted in a sheet that measured approximately 8 × 2 × ⅛ in. (203 × 51 × 3 mm). A ⅛ in. (3 mm) thick sheet of the yttriated Ti-5522S along with a ⅛ in. thick sheet of Ti-64 alloy, which was not yttriated, completed the materials that were employed in this study.

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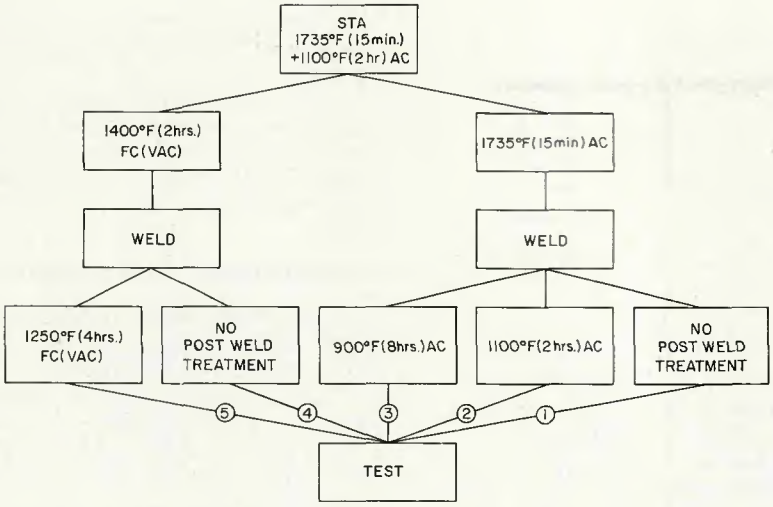


Fig. 1—The five metallurgical histories of this study

The amount and size of the non-yttriated Ti-5522S alloy dictated specimen sizes and testing throughout this investigation. The Ti-64 alloy was included as a control and by way of comparing the weld properties of the two forms of Ti-5522S to that of the more readily accepted Ti-64.

The yttriated Ti-5522S was in the solution treated and aged (STA) condition. This heat treatment was: 1735 F (945 C)—15 min AC + 1100 F (590 C)—2 h. In order to standardize the initial conditions, the non-yttriated Ti-5522S and Ti-64 alloy sheets were also given the STA treatment. Each of the three alloys was divided so that test specimens from each of five metallurgical histories were made available for mechanical testing and metallographic examination.

The five histories are most readily seen by reference to Fig. 1. Metallurgical histories 1, 2, and 3 were chosen in order to parallel the data reported by Hall, *et al.*[1] Histories 4 and 5 were chosen to parallel the data reported by Day.[6]

Each of the three alloys was subjected to full penetration bead-on-plate (BOP) welding by an automatic constant voltage (10 V) GTA welding unit. The weld conditions were dictated by the criterion of "bare penetration." Any number of combinations of weld traverse speeds and weld currents will result in a bare penetration BOP weld.

Rapid weld speeds, i.e., above 20 ipm, resulted in center line pile-up in the weldment; this, in turn, reduced the uniform thickness of the sheet. Relatively slow weld speeds—i.e., below 10 ipm—resulted in welds which could sustain no permanent deformation as ascertained by a hammer and vice technique. Thus, the standardized weld condition for this study was 225 A at 15 ipm (6.4 mm per s).

In order to minimize end losses and thus conserve the non-yttriated Ti-5522S, these materials were welded by sandwiching each sheet between two sheets of yttriated material. Figure 2 shows both the face side and the root side which serves to exemplify the meaning of the term bare penetration.

When the metallurgical histories indicated in Fig. 1 were complete, metallographic specimens were prepared by use of 1μ diamond paste with a 0.05μ alumina final polish. Etching, where employed, was accomplished with Kroll's reagent. Charpy V-notch and tensile specimens (Fig. 3) were prepared and tested to ascertain fracture toughness and ultimate tensile strengths of the weldments.

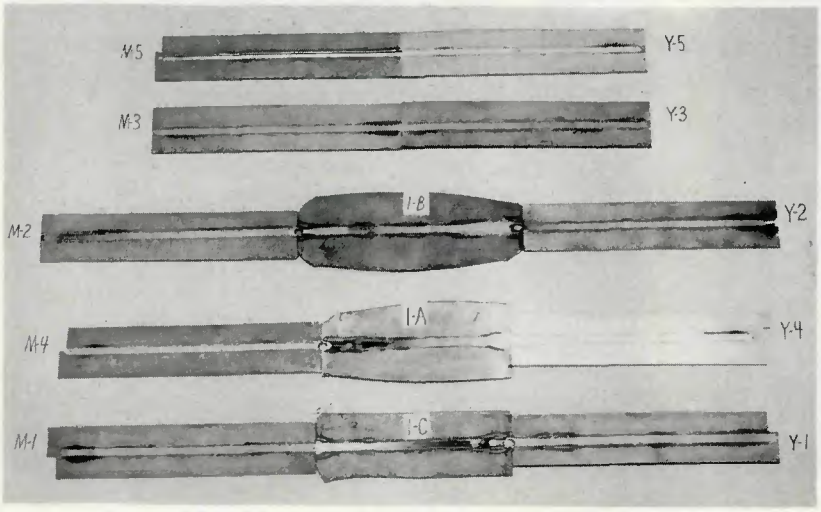
The slow bend Charpy V-notched specimens (notch centered on the weldment), were fatigue precracked over a span of 1.66 in. (42.2 mm) at maximum and minimum loads of 300 and 30 lb (136 and 13.6 kg), respectively. A crack length of 0.050 in. (12.7 mm) was minimum and usual. These specimens were then slow bend tested over a span of 1.66 in. (42.2 mm) at a constant cross-head speed of 0.01 ipm (0.004 mm/s). The tensile specimens, which were too small for determining other than ultimate strength, were tested under a constant cross-head speed of 0.02 ipm (0.008 mm/s). All specimens—both Charpy and tensile—were tested in a manner such that the center of the weldment face-to-root experienced the maximum stress.

Test Results

Table 1 lists all mechanical property test results. The data listed are indicative of several observations:

1. The data are reasonably consistent with previously reported physical properties.[2,5,6]

2. Reference to the data for yttriated Ti-5522S reveals that the weld metal, regardless of preweld or postweld heat treatment, displays a marked loss in toughness over that of the base metal. The data do not indicate any appreciable increase in ultimate tensile



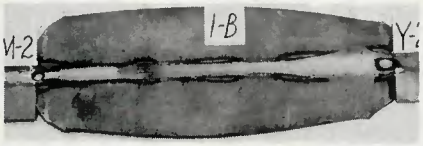


Fig. 2—BOP welded Ti alloy sheets: A (left)—face side; B (above)—root side

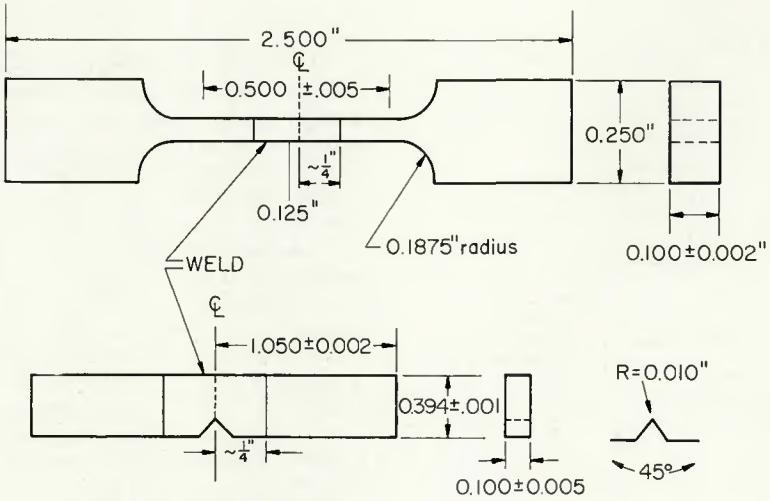


Fig. 3—Machine drawing of the tensile specimen and the Charpy V-notch specimen

strength.

3. Long postweld aging treatments, history number 3, may have deleterious effects on the toughness of all three alloys.

4. The non-yttriated Ti-5522S welds display good crack propagation resistance in the as-welded state. All of the postweld heat treatments employed in this study degraded this property.

5. For specimens which experienced no postweld heat treatment, the properties of the non-yttriated Ti-5522S welds compare favorably with the properties of the yttriated base metal.

Metallographic Observations

The metallographic study centers on three topics:

1. The manner of failure.
2. The probable cause of mechanical properties degradation.
3. The identification of that cause with the presence or absence of yttrium.

Metallographic examinations were made at several stages in the development of the five metallurgical histories. However, the Ti-64 alloy was processed as a control and observations of its weld metallurgy are not pertinent to the main topic. Also, since

Table 1—Strength and Toughness Properties

	Yttriated Ti-5522S		Non-Yttriated Ti-5522S		Ti-64	
Metallurgical history number	UTS,[b] kpsi	K_Q,[b] kpsi $\sqrt{\text{in.}}$	UTS,[b] kpsi	K_Q,[b] kpsi $\sqrt{\text{in.}}$	UTS,[b] kpsi	K_Q,[b] kpsi $\sqrt{\text{in.}}$
1[a]	170.7	30.2	160.8	54.4	146.9[c]	82.2
	171.8	39.8	168.0[c]	55.8	144.7[c]	62.5
2	164.6	34.2	176.1	36.7	122.5	65.9
			171.2			
3	176.9	28.4	180.3	36.1	148.0	28.8
				27.9		35.7
4[a]	157.1	28.9	163.3	62.8	138.1	58.2
		43.2				56.6
5	143.3	36.0	156.2[c]	42.3	131.9[c]	62.8
						66.6
1	160.4	65.8				
(Base metal) (no weld)	158.9	64.4				

[a]Histories which involve no postweld heat treatment.
[b]UTS—ultimate tensile strength; multiply by 6.894757 to convert to MPa. K_Q—fracture toughness; multiply by 1.0988SS to convert to $MN \cdot m^{-3/2}$.
[c]Indicates failure in the weld; all others failed in the base metal.

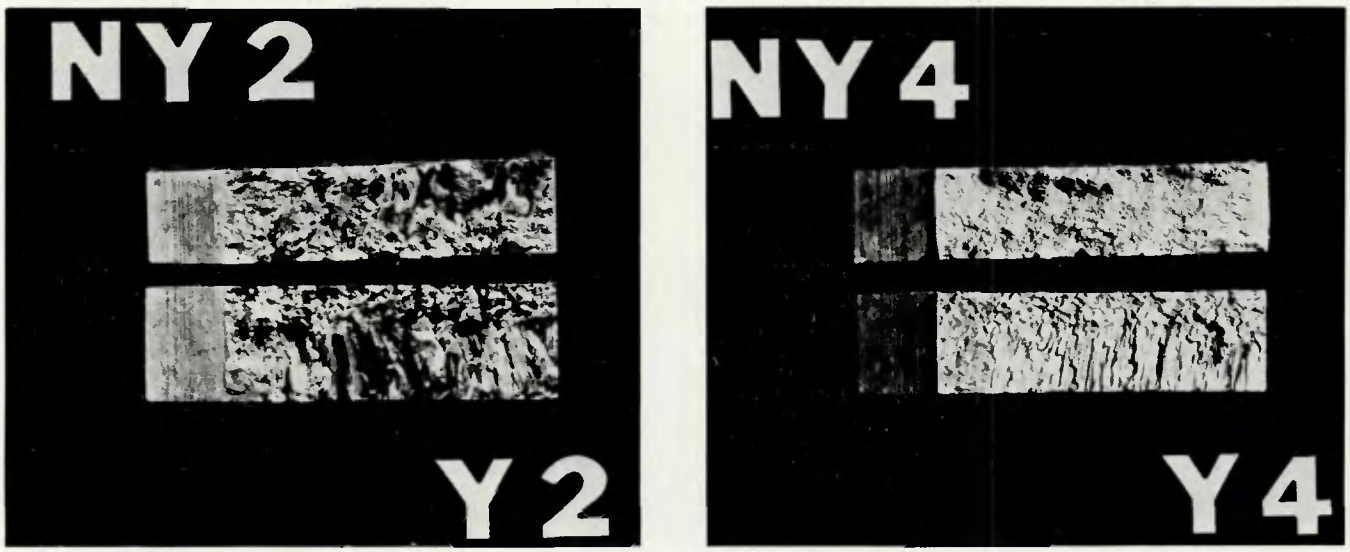


Fig. 4—Charpy specimen fracture surfaces which show gradations in intergranular failure

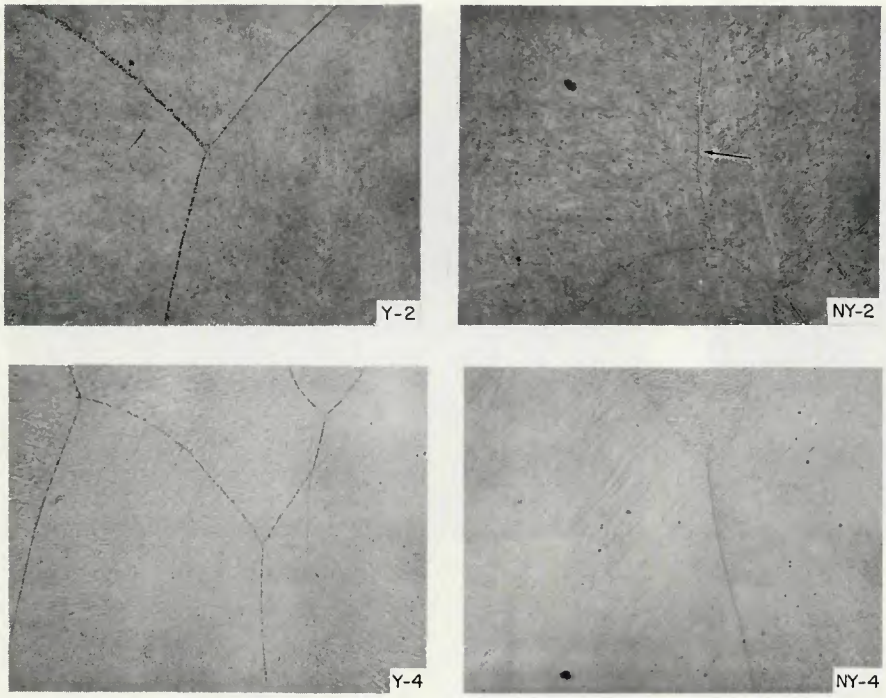


Fig. 5—Pertinent microstructures of Yttriated and Non-Yttriated Ti-5522S alloy. Kroll's etchant; ×200 (reduced 49% on reproduction)

Fig. 6—Grain boundary intersection in Yttriated Ti-5522S alloy. Kroll's etchant; ×2000 (reduced 37% on reproduction)

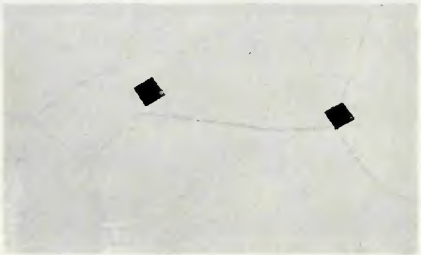


Fig. 7—Electron photomicrograph showing heavily decorated grain boundary with two microhardness indentation markers

only the metallurgy of the fractured welds are of interest here, the intermediate metallographic observations on the Ti-5522S alloys are not discussed.

The manner of failure is best shown by low magnification photographs of the fracture surfaces. Figure 4 includes such photographs of the slow bend Charpy specimens; it includes samples from histories 2 and 4 for both yttriated and non-yttriated Ti-5522S weldment fractures.

Comparison of Fig. 4 with the data of Table 1 reveals that low toughness values are associated with large prior beta grains and intergranular failure. The relatively high toughness of the non-yttriated Ti-5522S with no postweld heat treatment is marked by transgranular failure. From this observation, it appears that postweld heat treating of non-yttriated Ti-5522S causes degradation of the prior beta grain boundaries. It also appears that, when yttrium is added to the subject alloy, such grain boundary degradation is inescapable.

Figure 5 is a set of photomicrographs of the yttriated and non-yttriated Ti-5522S from histories 2 and 4. From these and the data of Table 1, it may be concluded that low toughness and intergranular failure in the yttriated material is provoked by a grain boundary phase which appears as a string of beads; each bead is about 0.1μ in diameter.

The low toughness and partial intergranular failure in the non-yttriated material is apparently caused by a continuous grain boundary phase which appears upon postweld heat treatment. When the Ti-5522S is not yttriated and no postweld heat treatment is performed, the grain boundary phase does not appear and the resulting weld is more crack propagation resistant.

Figure 6 is an electron-photomicrograph of a grain boundary intersection in yttriated Ti-5522S from history 2. The specimen had been etched with Kroll's reagent and, at this magnification, the grain boundary particles appear to be pores. Electron probes of these particles (pores) did not reveal any chemical segregation. This observation conflicts with scientific expectation as well as past observations.[5]

When the yttriated material was in the as-polished state, the bead-like boundary phase was not visible by either light or electron microscopy. This observation caused the suspicion that the beads could be solid phases which were either washed or dissolved out when the specimen was etched. In order to test this hypothesis, the following procedure was instituted:

1. Polish and etch a yttriated specimen.
2. Mark a heavily decorated grain boundary and a particle colony (sometimes present) by a microhardness indentation.
3. Repolish the specimen and use the hardness indentations as markers for energy dispersive x-ray area analysis.
4. When the EDX analysis work is complete, reetch the specimen to ascertain whether the probe was scanning the particles of interest.

Figures 7-9 contain representative results of the above described efforts. The element distributions shown were determined by conventional energy dispersive/wave length dispersive techniques. The etched photomicrograph of a heavily decorated grain boundary and its microhardness indentation markers may be seen in Fig. 7. The results of the energy dispersive X-ray analyses may be seen in Fig. 8. The lower right photographs in Fig. 8 are back-scattered electron images of the field of analysis; these serve to show the smoothness of the polished surface and the position of one of the micro-indentations. The other indentation would appear in the upper left, if the field of analysis were bigger. Thus, the grain boundary of interest proceeds from the lower right to the upper left in the field of view. It should be noted that the grain boundary does not appear to be associated with any chemical segregation.

Figure 9 is a view of the reetched specimen and shows that whatever phenomenon is causing the appearance of the beads upon etching must have been there during the chemical analysis. Yet, it did not show as chemical segregation.

A brief word is in order concerning resolution. The following discussion

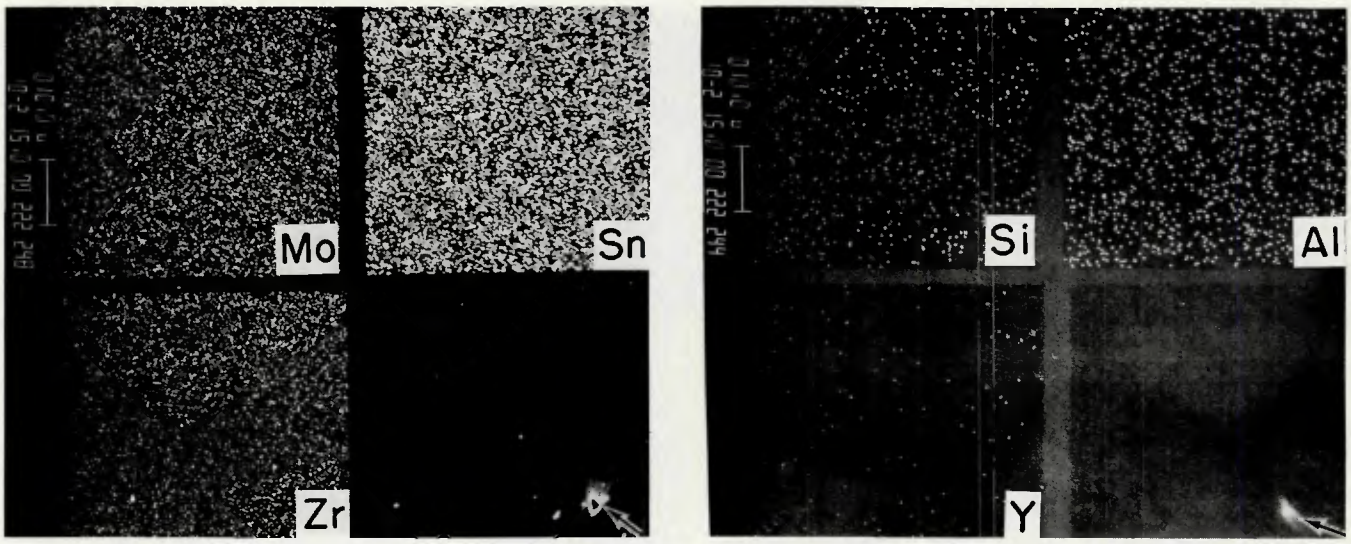


Fig. 8—Energy dispersive X-ray scans for ascertaining chemical segregation in Yttriated Ti-5522S alloy (also see Fig. 7)

would apply to any specie but concentrates on Y_2O_3. Suppose that the bead-like phase were provoked by yttria particles that were etched out and their cavities expanded. Furthermore, suppose that such particles were spherical and had radii of 0.1 μ. From density data and the fact that the alloy contains 250 ppm yttrium, it may be shown that the formation of such a particle would provoke total yttrium depletion in a surrounding sphere of 3.5 μ diameter. Thus, if such were the case, the grain boundary would appear as a 3.5 μ wide depleted path stretching diagonally across the field of view. Such a path would be apparent in Fig. 8, but it is not. Therefore, if such particles exist, they must be significantly smaller than 0.1μ in radius.

The foregoing does not prove that the deleterious grain boundary phenomenon that is associated with yttrium is not accompanied by segregation of that element. It does, however, constitute strong evidence for the truth of such an assertion.

On the basis of the evidence presented here, the bead-like boundary phase appears to be either a hole which is covered with disturbed metal in the as-polished state, or it is a high local strain energy site which etches preferentially. This conclusion is supported by Fig. 10.

Figure 10 is a high magnification electron photomicrograph of a yttriated Ti-5522S weld fracture surface. With reference to the dimpled surfaces in this photomicrograph, it is unlikely that the pits were ever filled with solid precipitate because, if so, at least a few of the particles would have remained imbedded in the fracture surface. One is then led to believe that most of the fracture surface dimples are, in fact, fractured pores.

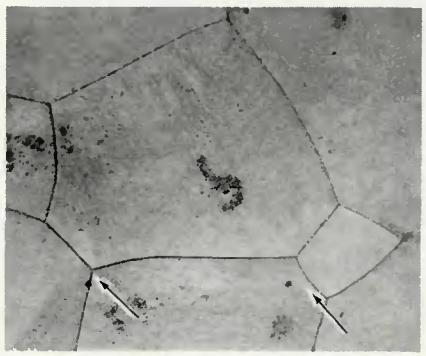


Fig. 9—Re-etched specimen (compare with Figs. 7 and 8)

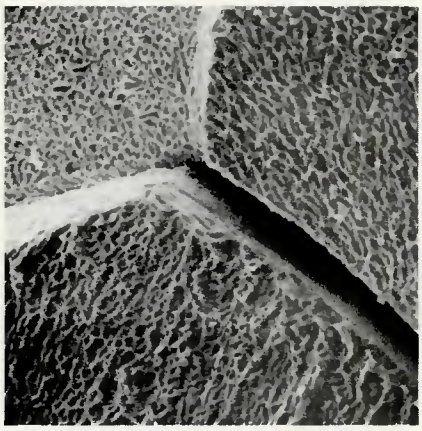


Fig. 10—Weldment tensile fracture surface in Yttriated Ti-5522S alloy; ×2000 (reduced 38% on reproduction)

Conclusions

1. It is possible to GTA weld Ti-5522S alloy such that the resulting weld has good efficiency provided that the material is not doped with yttrium and no postweld heat treatments are imposed.

2. GTA welds in Ti-5522S alloys which contain yttrium would seem to have poor toughness regardless of preweld or postweld heat treatments.

3. Although a bead-like grain boundary is present in all yttriated Ti-5522S welds and such a phase is deleterious to the mechanical properties of the weld, there is no evidence that this phase is a result of yttrium segregation to the grain boundaries.

Acknowledgments

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References

1. Hall, G.S., Seagle, S.R., Bomberger, H.B., "Development of a 900°F Titanium Alloy," AFML-TR-73-37, April, 1973.

2. Baczek, M.J., Hall, G.S., Seagle, S.R., Bomberger, H.B., "Grain Refinement in Titanium Alloys," AFML-TR-74-255, November, 1974.

3. Lewis, R.E., and Wu, K.C., "A Study of Weld Heat-Affected Zones in the Titanium 6Al-6V-2Sn Alloy," *Welding Journal*, 42 (6), June 1963, Research Suppl., pp. 241-s to 249-s.

4. Simpson, R.P., and Wu, K.C., "Microstructure-Property Control with Postweld Heat Treatment in Ti-6Al-6V-2Sn," *Welding Journal*, 53 (1), Jan. 1974, Research Suppl., pp. 13-s to 18-s.

5. Simpson, R.P., "Controlled Weld-Pool Solidification Structure and Resultant Properties with Yttrium Inoculation of Ti-6Al-6V-2Sn Welds," *Welding Journal*, 56 (3), Mar. 1977, Research Suppl., pp. 67-s to 77-s.

6. Day, D.L., "Evaluation of Ti-5Al-5Sn-2Zr-2Mo-0.25Si Titanium Alloy Sheet," Rockwell International Rep. No. NR75H-117, Aug., 1975.