Beta Titanium Alloys in the 80's

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Ti-3Al-8V-6Cr-4Mo-4Zr WIRE FOR SPRING APPLICATIONS

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Abstract

Presently high strength titanium alloy springs are fabricated from Ti-13V-11Cr-3Al. This has been a satisfactory spring material but it is a very difficult alloy to fabricate into wire, from the standpoints of melting and conversion from ingot to billet to hot roll stock to final wire size. This results in limited sources, high cost and, at times, lead time problems. Ti-3Al-8V-6Cr-4Mo-4Zr is an alloy developed by RMI which should present fewer fabrication problems which translates to lower cost, with fatigue properties equivalent or superior to the Ti-13-V-11Cr-3Al alloy. An extensive program was undertaken to evaluate the fatigue characteristics as a function of processing. Data will be presented correlating fatigue properties to the amount of cold work, grain size, surface finish, tensile strength and shot-peening intensity. Comparisons to Ti-13V-11Cr-3Al processed in accordance with AMS 4959 will be made.

Introduction

History

The evaluation of titanium as a spring material originated in the mid-1950's shortly after the first high strength beta titanium alloy was developed and patented in 1956. This Rem-Cru alloy known as B120VCA (Ti-13V-11Cr-3Al), had a low modulus ($<15 \times 10^6$ psi (103.4 GPa) elastic and $<6 \times 10^6$ psi (41.4 GPa) shear) and a high fatigue strength, and could achieve yield strengths in excess of 250 ksi (1724 MPa) in wire form. In the 1960's, this combination of properties made B120VCA a logical choice as a spring material in high performance internal combustion engines and assorted aerospace applications. However, processing difficulties with the alloy soon became apparent. Alloy segregation due to the high amount of beta stabilizing elements was a problem. Also, wire manufacture and spring fabrication exhibited erratic performance. In wire manufacture, the rolling and drawing processes were unable to be tuned in such a way as to allow high yield manufacture or consistent achievement of property goals. However, the weight saving potential and performance capability potential of B120VCA was so great that by 1965 the wire and spring industries had begun to resolve their production problems and Douglas Aircraft was evaluating springs for use on their soon to be introduced DC-10 widebody aircraft. By 1970 when the first DC-10 rolled off the line, it contained the first commercially used high strength beta alloy titanium springs, including the nose and main landing gear down lock springs, elevator and aileron control springs.

By the late 1960's, the two decade old titanium industry had matured enough to begin creating new titanium alloys to compete with the workhorse alloys of the 1950's. One area where this competition became keen was in the high strength spring alloys. One of the most successful competitors to B120VCA was the RMI alloy Ti-3Al-8V-6Cr-4Mo-4Zr (38-6-44). This alloy, patented in 1971, was touted as being capable of achieving those same high fatigue and yield strength levels, while retaining the low shear and elastic moduli. In addition, by the late 70's this alloy, also known as Beta C, was found to have fewer fabrication problems in producing wire than B120VCA, thus leading to much higher product yields. Evaluations of 38-6-44 were under way at McDonnell Douglas, Lockheed and Boeing for aerospace quality springs and at Ford Motor Company for automotive quality springs. The aerospace evaluations had identified the need for alternate sources as well as the hope for reduced cost through improved product yields. These spring alloy evaluations are continuing today, still attempting to identify one alloy as the best for use as a spring material.

Wire Fabrication

A brief discussion of the wire making process provides some insight into potential problem areas. The starting ingot is worked down to round cornered square billet in the size range of 2 1/4 to 3 1/4 in. (57-83 mm). This is then hot rolled to provide hot rolled coil or hot rod. This hot rod is the starting stock for the wire drawing operations. The mill scale must first be removed, mechanically or chemically, and the hot rod inspected. It will then be given a rounding pass through draw dies to true up the surfaces.

The surface would then be shaved prior to the wire drawing for defect removal. Test loops may then be drawn to determine the amount of cold work necessary to achieve properties. The hot rod is next drawn down to the final wire size in a series of steps involving drawing, surface cleaning, and inspection. The final anneal will be accomplished with the wire at a predetermined size to enable drawing to the final wire size with the intended amount of cold work, normally about 35%. The surface will once again be cleaned. The wire is then 100% visually inspected in conjunction with fluorescent penetrant and or Eddy-current techniques. The final steps are end product hydrogen analysis and properties certification.

There are many steps in the above operations which are critical in producing wire from which to fabricate usable springs. One of the first problems is elimination of the rolled seam on the hot rod. If it is not completely removed, cracks could propagate along the seams during wire drawing. Cold work prior to and after the final solution treatment or anneal is important. Insufficient cold work prior to the final anneal may prevent recrystallization; this would result in a large grain size, poor heat treat response and reduced fatigue properties. Partial recrystallization would result in heterogeneous heat treatment response along the length of the wire which creates problems for the spring fabricator, i.e., uniform coil diameters within a spring cannot be or are difficult to produce.

Care must be taken to assure proper maintenance of the draw dies so the wire surface does not get scored. Hydrogen pick-up must be avoided during the chem-mill or pickling operations as well as during heat treatment. If the final surface finishing operation is centerless grinding, care must be taken that heat build-up is minimal to prevent any oxide formation.

These are all common sense considerations but they have all contributed to the rejection of production wire lots.

Procedures

The 13-11-3 alloy was used for a baseline comparison as it is presently the primary high strength titanium spring material. The wire sizes, alloy melter and wire producer for each lot of wire studied are indicated in Table I. The materials were supplied at no charge as part of a joint data sharing program. The chemical composition of each material conformed to the limits of the appropriate specification.

The 13-11-3 baseline alloy wire was processed to meet the requirements of AMS 4959. Processing parameters of the 38-6-44 alloy were varied to attempt to optimize fatigue performance, which is the critical design requirement. The processing variables studied most extensively included: (1) the amount of final cold work, (2) tensile strength, (3) shot peening intensity. A cursory study was also made on the effects of the surface finish and grain size.

Tensile tests were performed on as-drawn wire (no reduced gage section) and machined specimens in accordance with the procedures of ASTM E-8. Fatigue tests for the screening studies were accomplished using 3-point bend specimens with a supported length of 4 in. (102 mm). Testing was done on a Sonntag SF-10U at a frequency of 30 Hz, a maximum stress of 150 ksi, and an R ratio (σmin/σmax) of 0.1. A 50 kip MTS machine was used to fatigue test the prototype production springs. The springs were tested at a frequency of about 1 Hz and an R value of 0.53.

The fatigue test conditions for the screening tests were much more severe than would be experienced in actual service. The reasons for this are two-fold. First, testing of the spring wire using the bend test under actual service conditions would result in fatigue lives running from tens to hundreds of millions of cycles, which would require more test time than available. Secondly, when dealing with lives of that duration scatter normally becomes a greater problem, and discriminating between the various conditions becomes more difficult. The 150 ksi (1034 MPa) maximum cyclic stress at an R of 0.1 results in a good life range for test purposes; from tens of thousands of cycles at the low end to lives under optimum conditions in the millions of cycles.

TABLE I - Wire Sizes and Producers for Each Alloy Investigated

Alloy	Wire Dia., in. (mm)	Cold Work %	Melter	Wire Producer
Ti-3Al-8V-6Cr-4Mo-4Zr	.229 (5.8)	37	RMI	Astro Metallurgical Corp.
1/	.312 (7.9)	33		Astro Metallurgical Corp.
	.350 (8.9)	35		Titanium Wire Corp.
	.353 (9)	35		Astro Metallurgical Corp.
	.392 (10)	35		Astro Metallurgical Corp.
Ti-3Al-8V-6Cr-4Mo-4Zr	.392 (10)	50	RMI	Astro Metallurgical Corp.
Ti-13V-11Cr-3Al 2/	.376 (9.6)	35	TMCA	Astro Metallurgical Corp.
Ti-13V-11Cr-3Al	.392 (10)	35	RMI	Astro Metallurgical Corp.

1/ MIL-T-9047, chemistry only

2/ AMS 4959

Results and Discussion

Screening Tests

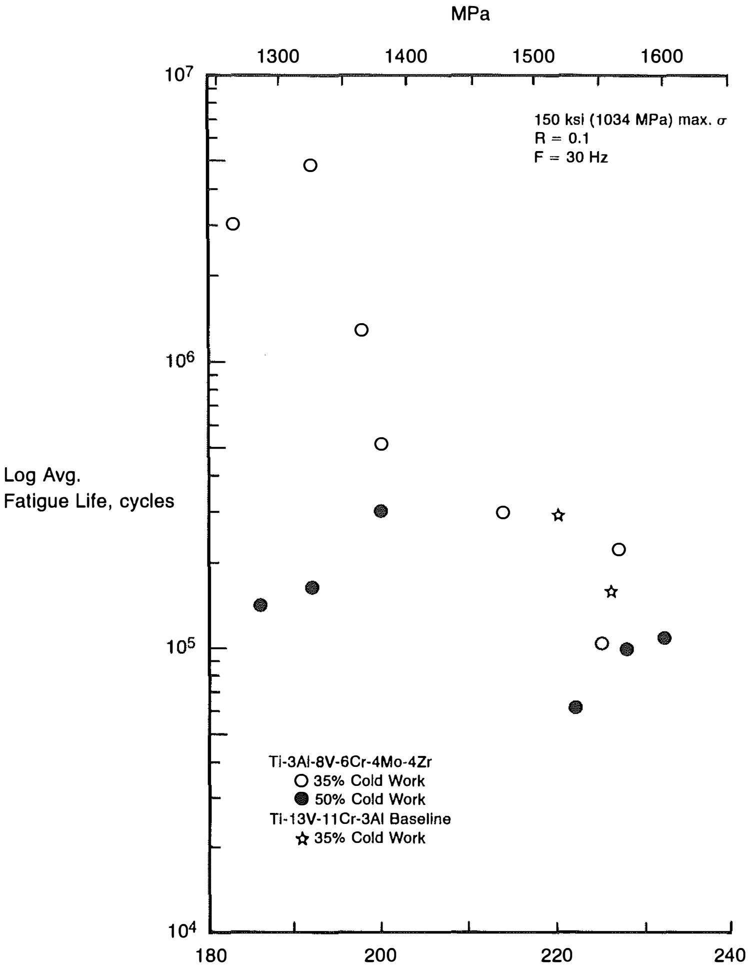
The intention of the screening phase was to optimize the processing parameters enabling selection of the best processing route from which to produce production springs for fatigue testing.

The amount of final cold work in conjunction with the strength level were felt to be the most important variables. A broader range of cold work levels of the 38-6-44 wire would have been desirable but were not obtained for various reasons. The wires were heat treated to strength ranges from about 180-235 ksi (1241-1620 MPa). Systematic tensile strength fatigue life data on the 38-6-44 wire was obtained at 2 cold work levels, 35 and 50%. The fatigue data derived as a function of tensile strength is displayed in Figure 1. The trend observed is interesting in that historically titanium spring wire has been heat treated to the maximum achievable strength. This data indicates that lower tensile strengths provide improved fatigue performance. The effect is dramatic for the 35% cold worked material. No real trends could be attached to the 50% cold worked wire, but in very general terms it appears that the lower strength is also beneficial for that condition, though to a rather minor extent. This general improvement in fatigue performance at the lower strength level is attributed to the increased ductility and decreased notch sensitivity of the lower strength condition. Notch sensitivity is considered important; even though springs are shot peened the surface condition is not always as good as would be desired and, surface imperfections would be important at high stress levels.

For the 38-6-44 alloy, the higher cold work level (50%) appears to be detrimental. It had consistently shorter fatigue lives than the 35% cold work at all strength levels, and the data was very erratic.

The next major consideration in the control or improvement of the fatigue performance of springs is the shot peening intensity. This was studied in detail for the 13-11-3 alloy. The fatigue life increases as shot peening intensity increases up to an Almen intensity of 0.010A. It then levels out, and again increases gradually at intensities greater than 0.014A (Figure 2). Associated Spring has a proprietary shot peening process and do not divulge the Almen intensities achieved, but it is assumed to be greater than 0.008 C intensity, and demonstrates that saturation has not yet occurred.

Another factor in fatigue performance is surface finish; this factor is difficult to improve over current practice without a significant increase in material price. A quick look at the effect of surface finish is presented in Figure 3. Fortunately the influence of surface finish is not significant at realistic operating stress levels. However, when the stress is very high a lathe turned finish can provide an order of magnitude improvement in fatigue performance even though the surfaces are shot peened.



a)

Figure 1. The effects of cold work and tensile strength on the log avg. fatigue life of a) Ti-3Al-8V-6Cr-4Mo-4Zr, 0.392 in. (10 mm) dia., shot peened to 0.016-0.018A. Each data point represents the log avg. of 6 tests. Ti-13V-11Cr-3Al data points included for comparison.

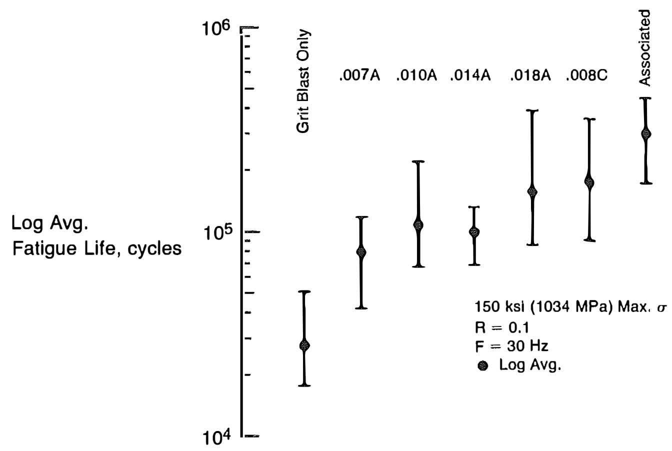


Figure 2. The effect of shot peening intensity on the fatigue life of 0.376 in. (9.6 mm) dia. Ti-13V-11Cr-3Al wire. Nine data points per test condition.

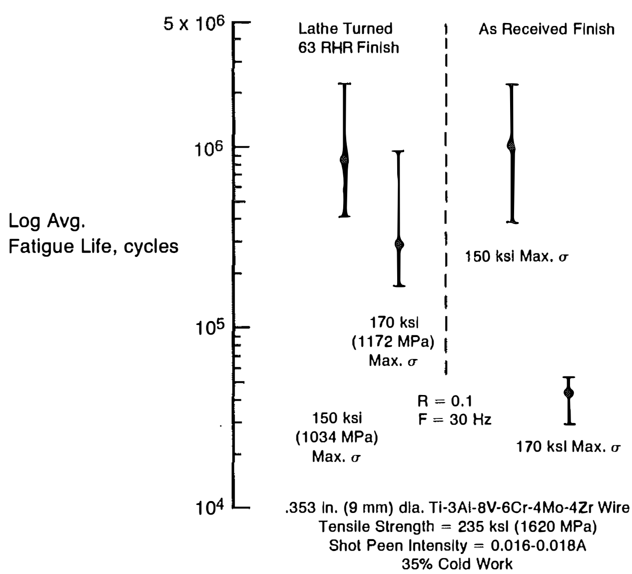


Figure 3. The effect of surface finish prior to shot peening on fatigue life at two stress levels for 0.353 in. (9 mm) dia. Ti-3Al-8V-6Cr-4Mo-4Zr wire. Six data points per test condition.

It was not possible to systematically study the effect of grain size on fatigue performance because the grain size of the wire received did not vary over a broad enough range. However, one extreme example was observed which does illustrate that some grain size control is required. One lot of wire was obtained which was not recrystallized. Figure 4 illustrates the microstructure of that material along with a more typically observed recrystallized microstructure. As can be seen in Figure 5 the unrecrystallized structure resulted in a lower fatigue life. The lack of recrystallization was ascribed to insufficient cold work prior to solution treatment.

Summarizing the screening tests, 38-6-44, when used at a reduced strength level could be processed to provide an order of magnitude increase in fatigue life over the baseline 13-11-3 alloy. Utilization of 38-6-44 at strength levels comparable to 13-11-3 yielded similar fatigue lives. Fatigue improvements of similar magnitude could probably be achieved by using 13-11-3 at the reduced strength level.

The 35% cold work level provides fatigue properties significantly superior to wire cold worked 50%. The reason for this is not understood.

Shot peening is a critical parameter and shot peen intensities of at least 0.016-0.018A should be used. Higher intensities would provide additional improvement in fatigue life, but a higher intensity call-out could limit the number of shot peening sources available due to equipment limitations.

Control of grain size is required but has not been quantified. As a minimum the wire should be recrystallized during solution treatment.

Production Springs

Eight prototype production springs were fabricated from 38-6-44 wire cold worked about 35%. Four each were heat treated to about 180 and 200 ksi (1241 and 1379 MPa) for fatigue testing (as this would be the anticipated strength range used) and shot peened at 0.016 to 0.018A. The spring design was that of a compression spring (Figure 6) presently in production made from 13-11-3 wire. The wire diameter is 0.312 in. (7.9 mm) with a coil diameter of 1.9 in. (48.3 mm) and a spring height of 6.25 in. (159 mm). Four 13-11-3 production springs were procured and tested along with the 38-6-44 springs. These springs were heat treated to the 220 ksi (1517 MPa) strength level in accordance with AMS 4959. Testing was initiated at a 91.2 ksi (629 MPa) maximum stress with an R ratio of 0.53 which simulates service loading. All twelve springs went 500,000 cycles with no failures. The maximum stress was then increased to 103 ksi (710 MPa) with the same results. The maximum load was then increased to 118.6 ksi (811 MPa) and the springs ran 10^6 cycles with no failures.

The springs bottomed out at this point so it was not possible to determine, using these springs, if the 38-6-44 alloy is superior to the presently used 13-11-3 springs. These tests did demonstrate equivalency and the probability that either alloy could be used at higher stresses than normally called out. These results provide good confidence regarding titanium spring life with the margin of safety provided.

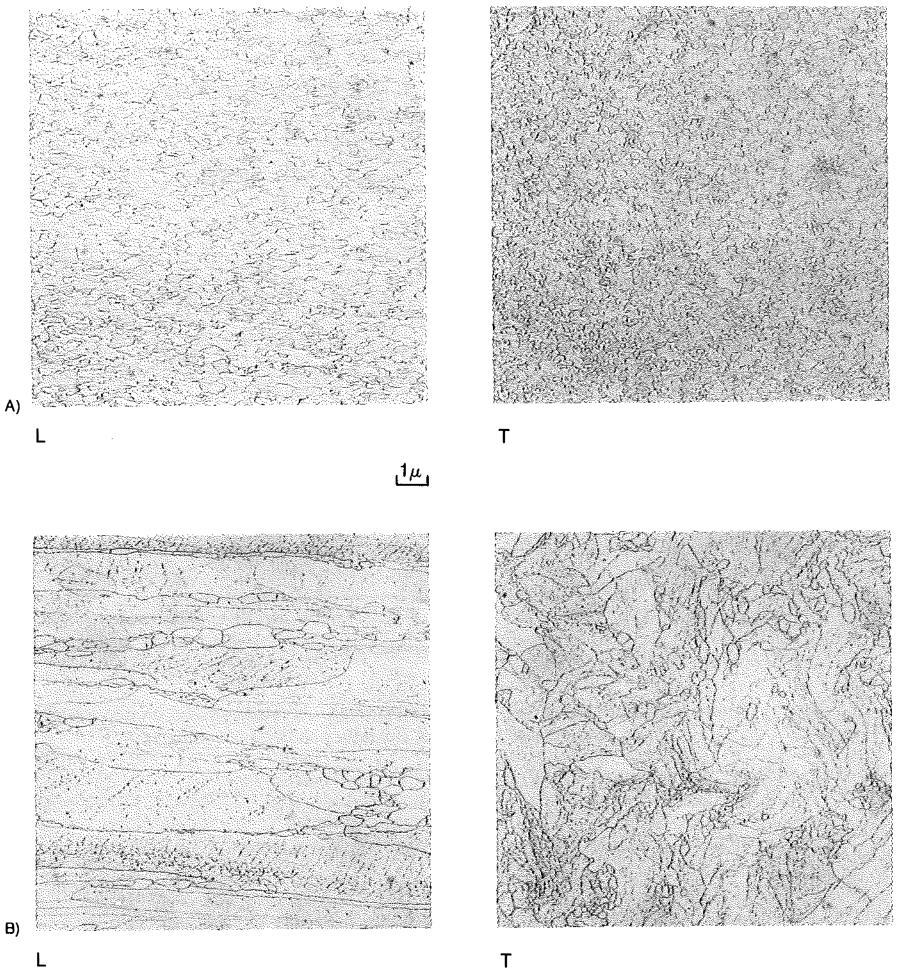


Figure 4. Microstructures of Ti-3Al-8V-6Cr-4Mo-4Zr wire in the a) recrystallized and b) unrecrystallized conditions. Microstructures correspond with the test material, figure 5.

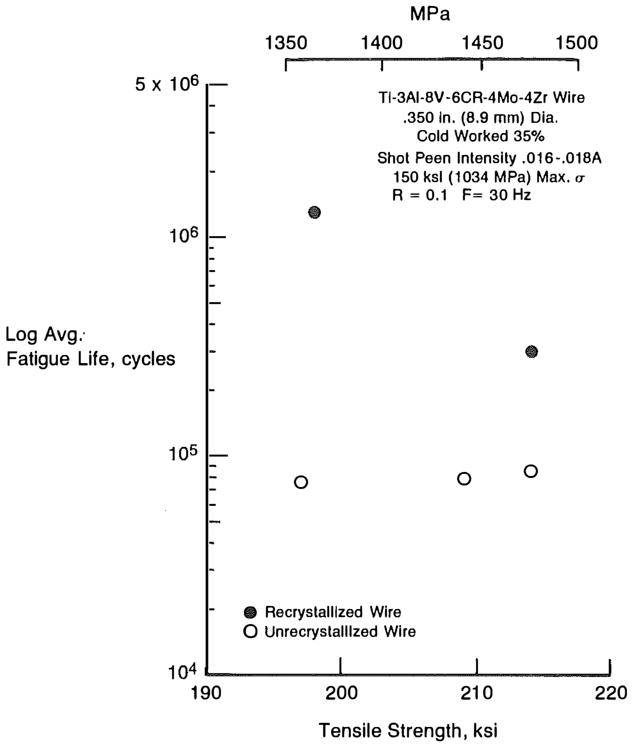


Figure 5. Fatigue life versus tensile strength for recrystallized and unrecrystallized Ti-3Al-8V-6Cr-4Mo-4Zr wire. Six data points per condition.

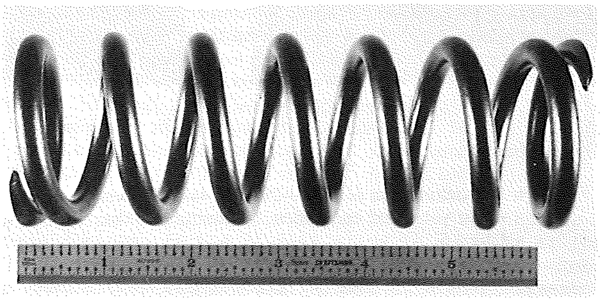


Figure 6. Prototype production springs fabricated for fatigue testing using Ti-3Al-8V-6Cr-4Mo-4Zr.

It should be pointed out that the reduced strength level studied for the 38-6-44 may not be appropriate for extension springs. Depending on design the stresses in the hook may be twice those developed in the coils. This could result in a service stress near the yield strength and greatly reduce the fatigue life of the spring.

Although improvements in fatigue performance similar to those shown with 38-6-44 could probably be attained by utilizing 13-11-3 at the lower strength level, the authors feel there are melting and fabrication advantages offered by 38-6-44 over 13-11-3. In addition, the presence of an alternate spring material should be beneficial to the end users.

Conclusions

1. Ti-3Al-8V-6Cr-4Mo-4Zr is a viable spring material which, when used at the 180-200 ksi (1241 to 1379 MPa) strength level, is equivalent or superior to Ti-13V-11Cr-3Al spring wire processed in accordance with AMS 4959.

2. Working at strength levels reduced from those normally used for high strength titanium springs provides an improvement in fatigue performance. This reduced strength level would not be recommended for tension spring applications due to the high hook stresses which could exist.

3. The 35% cold work level is recommended at this time. An investigation of the effect of lower cold work levels should be undertaken.

4. Shot peen intensities on the order of 0.016 to 0.018A or higher should be used to attain maximum fatigue performance.

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