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Single-Melt Beta C for Spring and Fastener Applications

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Beta C is a high-strength metastable titanium alloy widely used for spring and fastener applications. Input stock of these springs and fasteners is currently made by rolling billets forged from conventional double-melt VAR (2 × VAR) ingots. Recent advances in plasma arc melting (PAM) single-melt technology offer the potential to reduce the input stock cost by directly rolling as-cast near-net shape PAM ingots instead of the conventional forged billets. A 127 mm (5 in.) diameter as-cast Beta C PAM ingot was rolled into 15 mm (0.6 in.) bars for springs and fasteners. Microstructures and mechanical properties of the bar product are evaluated in this paper.

Keywords Beta C, PAM melt, springs

1. Introduction

Beta C (Ti-3Al-8V-6Cr-4Mo-4Zr) is a metastable β titanium alloy that can be solution treated and aged to achieve a good combination of tensile strength, fatigue strength, toughness, and ductility (Ref 1). Beta C can achieve strengths ranging from 830 to 1450 MPa (120-210 ksi), depending on the processing route and heat treatment. These high-strength levels are the result of the precipitation of very fine α during aging.

The thermomechanical processing route selected to produce wrought products has a significant effect on the final hot-worked microstructure, recrystallization behavior, and aging response (Ref 2). Metastable β titanium alloys have a narrow range of thermomechanical processing parameters that allows the final product to have a recrystallized uniform grain size (Ref 3). In addition, it is important that the process selected allows a uniformly aged product to be produced after the solution treatment and aging (STA) steps are applied. Beta C is a β-rich metastable β alloy that relies on heterogeneous nucleation of α during the aging treatment. It is prone to development of unaged or partially aged areas in regions that are completely recrystallized.

The unaged areas can have a significant effect on mechanical properties, especially fatigue and fracture toughness (Ref 4). Unaged areas can detrimentally affect fatigue performance when fatigue cracks initiate in the softer unaged material (Ref 5), whereas these same softer, small, well-dispersed unaged areas may increase fracture toughness (Ref 6). Unaged areas can be reduced or, in some cases, eliminated by duplex aging, where initial aging in the 420-460 °C (788-860 °F) range is followed by aging at higher temperatures to achieve the desired strength level (Ref 4). The initial age allows the solute-lean metastable β′ phase to develop via a phase-separation reaction. During the second step of the duplex aging process, α-phase precipitates on the β′, allowing a uniform α precipitation to result (Ref 5).

Although Beta C has great mechanical property capability, it is more expensive to produce than α-β alloys, such as the commonly used Ti-6Al-4V alloy. Most of the additional cost is

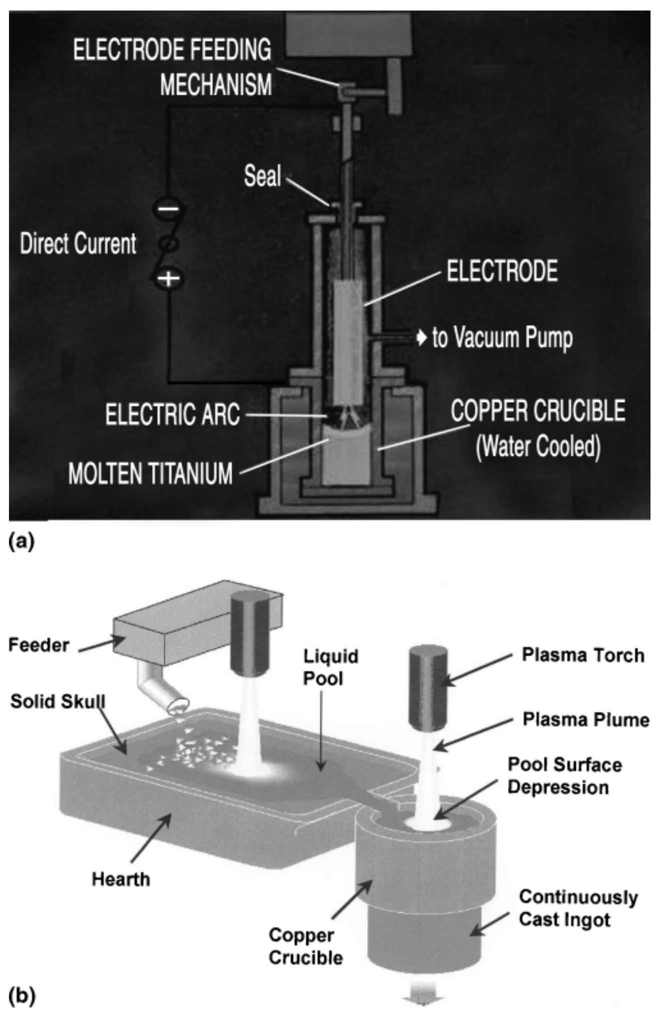

Fig. 1 Titanium melting processes; (a) Vacuum arc remelting (VAR); (b) Plasma arc melting (PAM)

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the result of more expensive alloy additions that make up 25% of the total composition of Beta C. One possible method to reduce the overall cost of Beta C product is to single-melt the alloy using plasma arc melting (PAM) to a smaller diameter ingot than is used in conventional double-VAR melting. Cost reductions utilizing this processing route include (a) more flexible use of raw materials and (b) significantly fewer hot working and conditioning steps to prepare the material for input to a bar-rolling mill.

A comparison of the VAR and PAM melting processes is shown in Fig. 1. The PAM process permits a more flexible use of various forms of low-cost input materials and requires only one melting operation whereas, the VAR process needs at least two melting operations to assure homogeneity.

Fewer hot working and conditioning steps are required during processing of the PAM material, resulting in a higher yield from ingot to bar rolling input. The processes for making bar from VAR and single-melt PAM are schematically shown in Fig. 2. The single-melt PAM process allows many processing steps to be eliminated.

2. Procedure

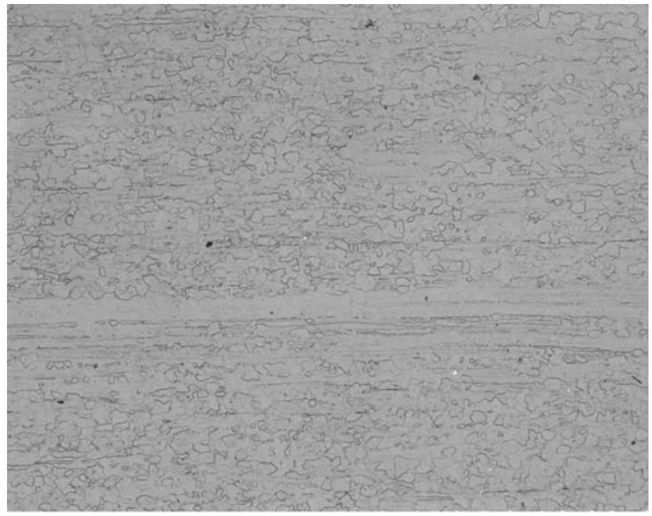
The 127 mm (5 in.) diameter single-melt Beta C PAM ingot was produced using the research PAM furnace at RMI (Niles, OH). The input material was titanium sponge and conventional master alloys. After melting, the ingot was turned and shipped to Dynamet (Washington, PA) for processing to 15 mm (0.6 in.) diameter hot-rolled bar product. The ingot was heated to 954 °C (1750 °F) and hot-rolled to bar without intermediate conditioning.

Heat treatments were performed using a range of solution treatment temperatures, 760-871 °C (1400-1600 °F). Selection of a solution treatment temperature was based on microstructural uniformity after aging the bar. Both direct aging and STA heat treatments were used for mechanical property evaluations.

Table 1 Chemistry of the 127-mm (5-in.) Beta C single-melt PAM ingot

	Chemical composition, wt.%				
	Al	V	Cr	Mo	Zr
Location					
Top	3.3	7.9	6.4	4.3	4.1
Bottom	3.4	8.4	6.5	4.4	3.4
AMS 4958	3.0-4.0	7.5-8.5	5.5-6.5	3.5-4.5	3.5-4.5

Tensile tests were conducted as per ASTM E8. Double-shear tests were conducted according to MIL-STD-1312 on two conditions, and fatigue tests, $R = 0.1$, 30 Hz, were run according to ASTM-E466 on the two heat-treated conditions selected.



(a)

(b)

Fig. 3 Microstructure of as-rolled 15 mm (0.6 in.) diameter Beta C bar rolled from 127 mm (5 in.) diameter single-melt PAM ingot; (a) longitudinal, edge, 100×; (b) longitudinal, center, 100×

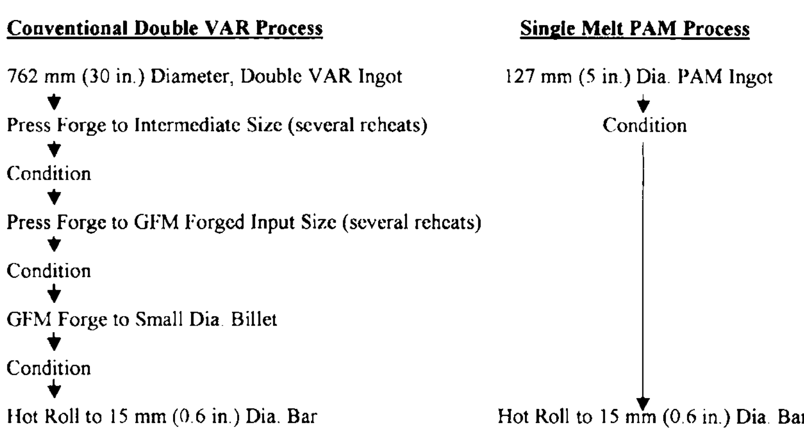
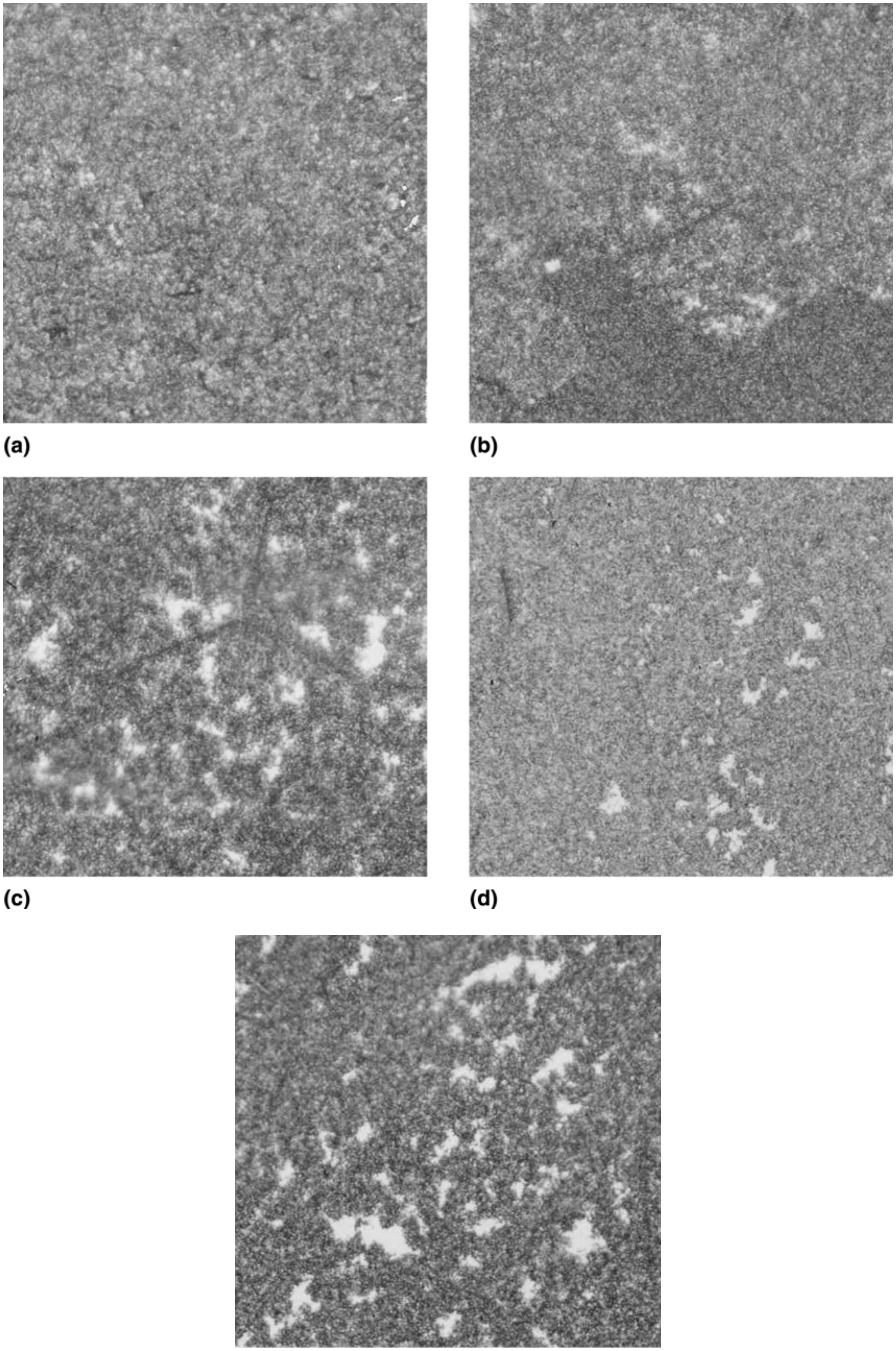


Fig. 2 Comparison of processing routes for Beta C bar produced using conventional double-VAR ingot and single-melt PAM ingot



(a) (b) (c) (d) (e)

Fig. 4 Effect of solution annealing temperature on microstructure of aged Beta C 15 mm (0.6 in.) diameter bar rolled from 127 mm (5 in.) diameter single-melt PAM ingot; (a) transverse, center, 500×, direct aged: 496 °C (925 °F)-24 h-AC (no solution treatment); (b) transverse, center, 500×, 760 °C (1400 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC; (c) tranverse, center, 500×, 788 °C (1450 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC; (d) transverse, 500×, 815 °C (1500 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC; (e) transverse, 500×, 843 °C (1550 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC

3. Results and Discussion

The chemical analyses of the ingot are shown in Table 1.

3.1 Microstructural Analysis

The longitudinal microstructures of the as-rolled bar are shown in Fig. 3 for center and edge locations. The edge showed a generally fine grain size with some evidence of a scattered unrecrystallized band. The center was mostly unrecrystallized in the as-rolled condition with few recrystallized grains shown. The unrecrystallized areas existed as elongated grains.

Transverse microstructures (center location) generated in the heat treatment study are shown in Fig. 4. The directly aged condition, 496 °C (925 °F)-24 h-AC, showed very uniform aging. This was also the case for the 760 °C (1400 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC condition. As the solution treatment temperature was increased to 788 °C (1450 °F) and higher, unaged or partially aged areas increased, which appear as white locations in the microstructure. These β areas

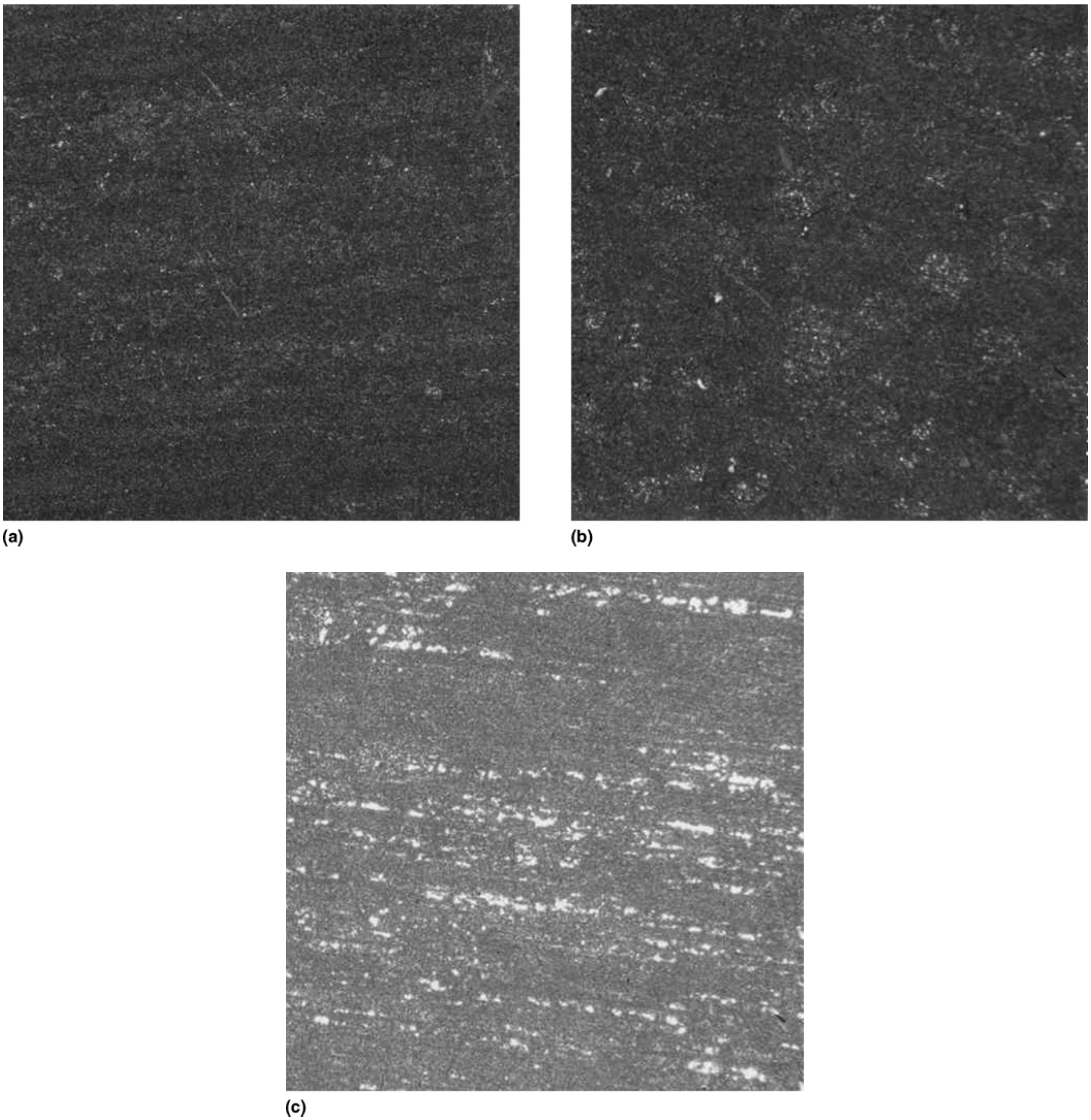


Fig. 5 Effect of thermal treatments on the microstructure of Beta C 15 mm (0.6 in.) diameter bar rolled from 127 mm (5 in.) diameter single-melt PAM ingot; (a) longitudinal, center, 100×, direct aged: 496 °C (925 °F)-24 h-AC; (b) longitudinal, center, 100×, STA: 760 °C (1400 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC; (c) longitudinal, 100×, 843 °C (1550 °F)-30 min-AC + 496 °C (925 °F)-24 h-AC

are the result of the minimization of substructure in the microstructure in these locations, thereby increasing the difficulty of α nucleation in these areas. Based on this study, it was decided that the lowest temperature should be used for solution annealing, 760 °C (1400 °F), in the mechanical property evaluation.

Figure 5 shows the longitudinal microstructures of the direct age, 760 °C (1400 °F) + age, and 843 °C (1550 °F) + age conditions. These microstructures support the conclusions from the transverse microstructures. The direct age and 760 °C (1400 °F) STA show very few unaged areas. After solution treating at 843 °C (1550 °F) and aging, the quantity of unaged areas increased substantially. These areas tend to be grouped in bands in the longitudinal microstructure.

3.2 Tensile Properties

Tensile properties are shown in Table 2. The as-rolled condition showed that the 15 mm (0.6 in.) diameter bar achieved moderate yield strength, 948 MPa (137.5 ksi), with excellent ductility, 28% elongation, and 46% reduction in area. Direct aging of the bar increased the yield strength to 1410 MPa (204.5 ksi), whereas lower yield strength was achieved in the bar after solution treating at 760 °C (1400 °F) and aging, 1103 MPa (160 ksi). Data is given for bar produced from a VAR ingot after solution treating at 815 °C (1500 °F) and aging for 20 h at 496 °C (925 °F). The yield strength of this material was 1185 MPa (172 ksi). The direct-aged PAM and STA VAR materials met the 1240 MPa (180 ksi) minimum UTS and 8% minimum elongation required by AMS 4958.

3.3 Double-Shear Evaluation

Double-shear strength data are plotted as a function of yield strength for 15 mm (0.6 in.) diameter Beta C bar produced from both single-melt PAM ingots and conventional VAR melts in Fig. 6. The data generated from the PAM bar is slightly above the trend line for the VAR bar developed in previous studies.

3.4 Fatigue

Fatigue data was generated at 1034 MPa (150 ksi) maximum strength, $R = 0.1$, and a cyclic rate of 30 Hz. The data are shown in Fig. 7 for both bars produced from PAM ingot and VAR ingot. The initial data were generated at the topmost portion of the fatigue curve, and the PAM data seem to lie within the portion of the curve that would be predicted based on STA bar from VAR ingot. Additional data will be generated near the endurance limit for Beta C bar.

4. Conclusions

- Beta C bar produced from single-melt PAM ingots is capable of meeting tensile requirements of AMS 4958: 1240 MPa minimum UTS and 8% minimum elongation.
- Double-shear values for Beta C bar produced from single-melt PAM ingots follow trends based on yield strength relationships for bars produced from VAR ingots.
- Fatigue data at high stress levels indicate similar performance for bars produced from VAR and single-melt PAM ingots.

5. Future Work

- Additional fatigue data will be generated at stress levels near the endurance limit.
- Additional tensile data will be generated using different solution treatment and aging temperatures.

Table 2 Tensile evaluation of Beta C 15-mm diameter bar hot-rolled from 127-mm diameter PAM ingot

Material condition	UTS, MPa (ksi)	0.2% YS, MPa (ksi)	Elongation, %	RA, %
As-rolled, PAM	985 (142.8)	950 (137.5)	28	46
Direct age 496 °C (925 °F)-24 h-AC, PAM	1555 (225.2)	1410 (204.5)	9	10
STA 760 °C (1400 °F)-30 min-AC, 496 °C (925 °F)-24 h, PAM	1215 (176.2)	1105 (160.0)	12	16
STA 815 °C (1500 °F)-1 h-AC, 496 °C (925 °F)-20 h-AC, VAR	1325 (192.0)	1185 (172.0)	11	28
STA req. AMS 4958	1240 (180.0) (minimum)		8 (minimum)	

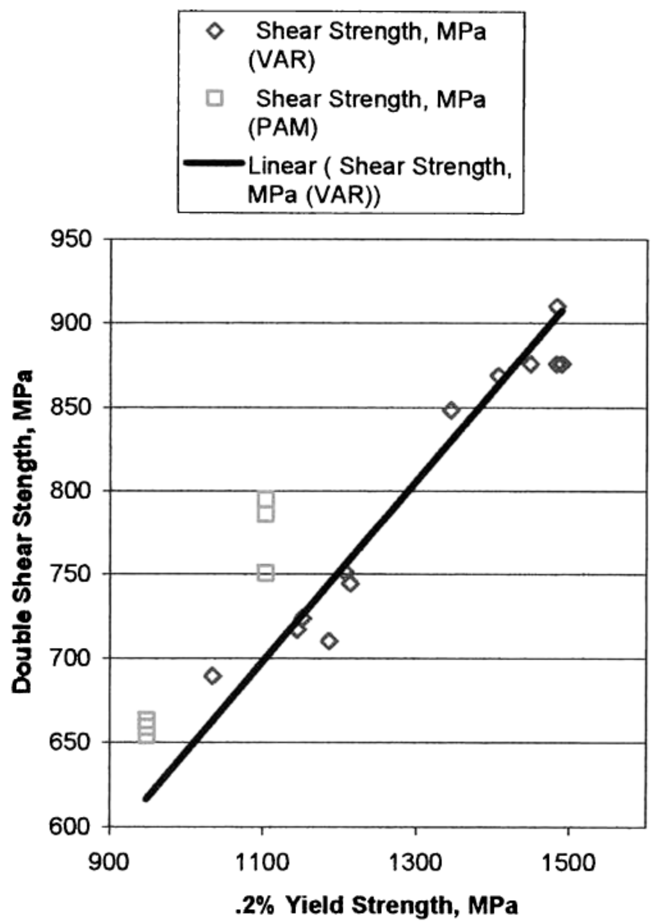


Fig. 6 Double shear strength of Beta C bar produced from VAR and single-melt PAM ingots

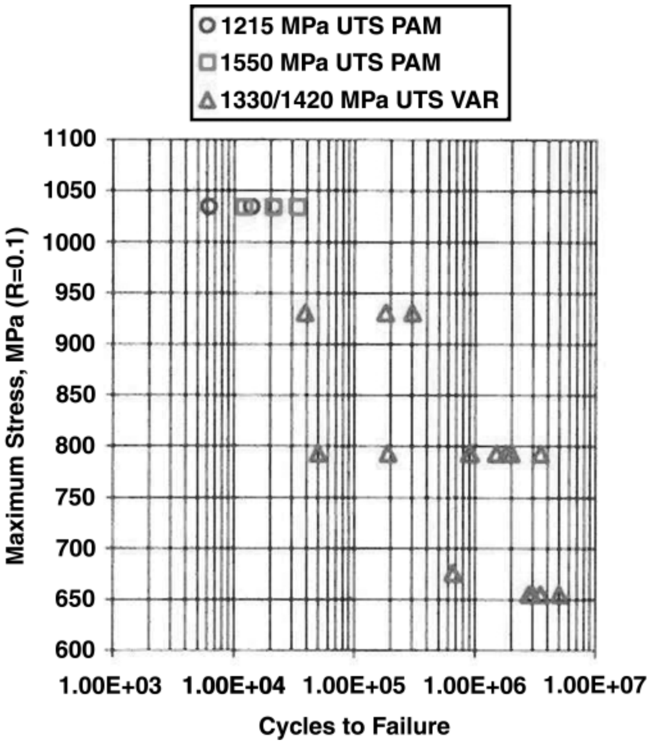


Fig. 7 Fatigue data for Beta C heat-treated bar produced from VAR and single-melt PAM ingots

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