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TECHNOLOGY

WHITE PAPER

CAST/WROUGHT VS. POWDER METALLURGY PROCESSING

Stronger, more durable and higher quality orthopedic implants with PM-processed BioDur CCM®

SUMMARY

For several decades, orthopedic medical implants were manufactured mainly from austenitic stainless steels, titanium and titanium alloys, and cobalt-based alloys. The selection of which alloy system to use for a specific application depended upon a variety of design criteria, including biocompatibility, corrosion resistance, tensile strength, fatigue strength, modulus, wear resistance, processing, and cost.

The vast majority of cobalt-based orthopedic implants worldwide have been manufactured using castings of ASTM F75 alloy. In many instances, castings provided desirable processing flexibility and lower initial costs. However, distinct limitations were associated with castings, such as coarse grain size, non-uniform microstructural segregation, and lower tensile and fatigue strength. These drawbacks can be overcome by manufacturing cobalt-based implants from cobalt-chromium-molybdenum wrought bar stock.

Of the three wrought Co-28Cr-6Mo (BioDur CCM) alloys covered under ASTM F1537 and used for orthopedic medical implants, the lowest-carbon (0.14% max) Alloy 1 (UNS R31537) has been utilized most frequently. This alloy is traditionally manufactured by conventional cast/wrought processing, but can also be manufactured using powder metallurgy (PM) processing.

Studies to characterize the differences in bar stock made by each of the two manufacturing methods revealed distinct advantages for the PM process, including higher strength, improved fatigue resistance, and enhanced microstructural characteristics at both room and elevated temperatures. Data collected confirmed that both methods of manufacturing wrought feedstock are superior to casting.

Carpenter Technology conducted the study by manufacturing its version of Alloy 1, Biodur CCM, by conventional cast/wrought processing and comparing it to the same alloy created by powder metallurgy (PM) processing.

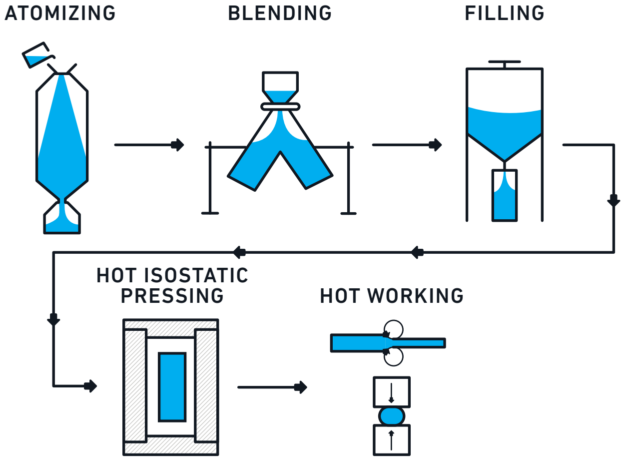
PROCESS

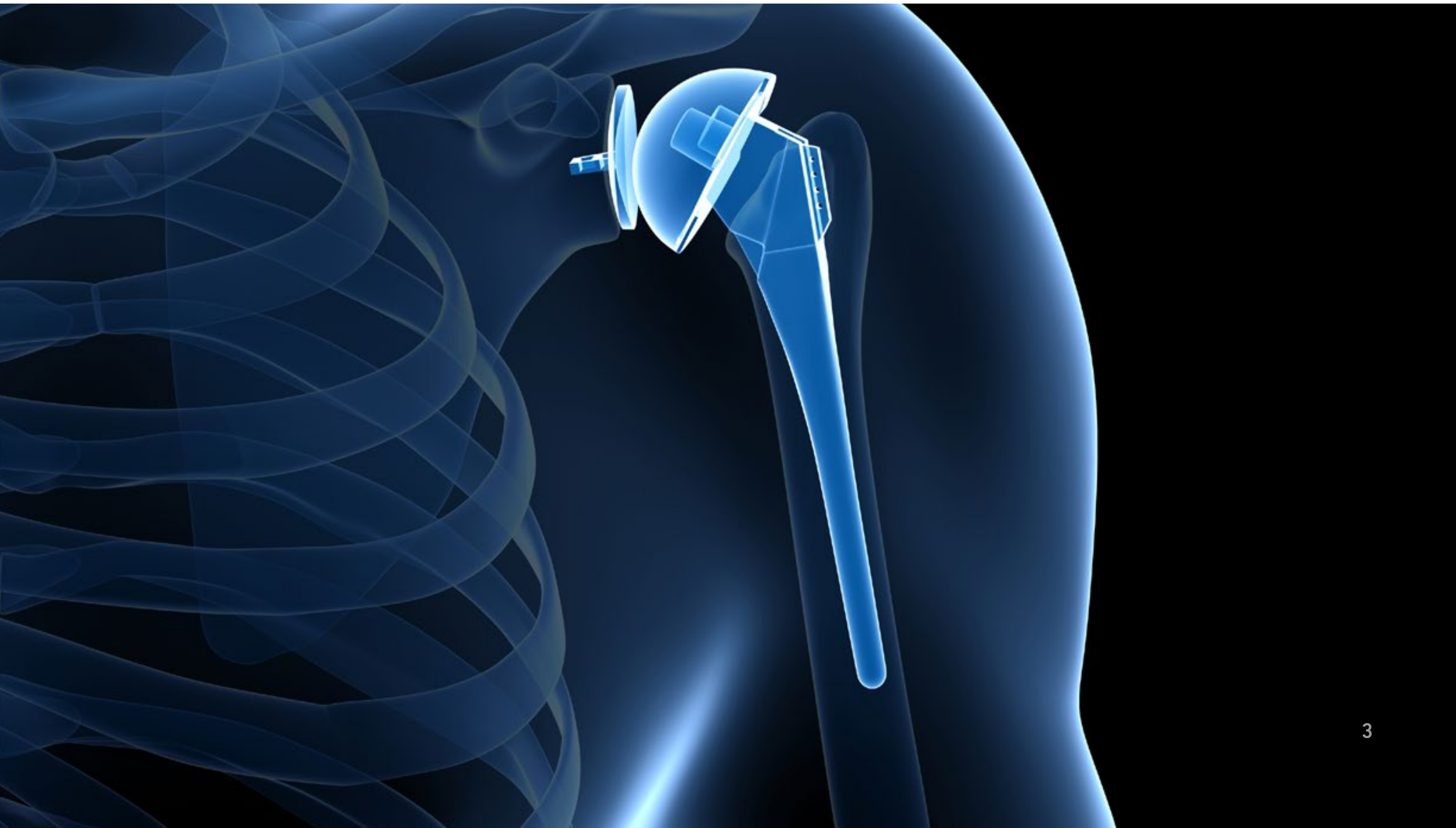
The conventional cast/wrought alloy is typically manufactured by vacuum induction melting (VIM), electro-slag remelting (ESR) ingots, hot forging to billets, hot rolling into wrought bar stock, then turning and grinding to finish condition.

In contrast, Carpenter Technology's powder metallurgy process is as follows (Figure 1):

- Vacuum induction melt a heat of high purity gas atomized powder
- Screen the powder to a predetermined mesh size
- Blend several heats to make one master blend
- Fill stainless canisters and hot isostatic press (HIP) to full denseness
- Hot roll into fully wrought bar stock
- Turn and grind to finish

FIGURE 1 — AN EXAMPLE OF THE MICRO-MELT POWDER METALLURGY PROCESS.





BENEFITS

When compared with the conventionally produced cast/wrought alloy, bar stock made by PM processing was found capable of higher tensile and fatigue strength, increased hardness, finer grain size, and more uniform structure less prone to segregation. These attributes were found in bars in the typical, as-supplied warm worked, unannealed conditions. However, the powder-processed alloy provided these same relative benefits after exposure to the elevated temperatures typically associated with annealing or forging of orthopedic implants.

> The unique advantages imparted by the PM process, when carried over to machined and forged components, are expected to improve the performance and life of joint replacement implants and fracture fixation devices, suchas total shoulder, hip, knee, and shoulder replacements.

The characteristics typically produced by PM processing allow the F1537 Alloy 1 (BioDur CCM) to be produced in the warm worked or hot worked unannealed conditions in smaller diameter bar and wire products than the conventional cast/wrought alloy. Also, powder-processed stock can be made without cold drawing and annealing, which can be detrimental to fatigue strength.

With fatigue strength superior to that of the cast/wrought alloy bar stock, PM bar stock could be considered for smaller-diameter applications requiring higher fatigue capability, such as pins, rods, and wire that are typical for some spinal applications.
The powder process should also allow for the production of fully wrought, near-net shapes for applications where higher tensile and fatigue strength are required than are possible with castings.

PROPERTIES

The conventional cast/wrought alloy is offered in the annealed or, more typically, in the hot worked or warm worked conditions. The powder-processed alloy is typically offered in either the annealed or, more commonly, the warm worked condition. When manufactured to the same metallurgical condition (such as warm worked), the PM alloy typically exhibits higher yield and ultimate tensile strength (Figure 2).

FIGURE 2

TYPICAL MECHANICAL PROPERTIES OF CONVENTIONAL CAST/WROUGHT ALLOY 1 AND PM ALLOY 1

PROPERTIES	CAST/WROUGHT ALLOY 1	CAST/WROUGHT ALLOY 1	POWDER METALLURGY ALLOY 1
	HOT WORKED	WARM WORKED	WARM WORKED
0.2% yield (ksi)	135	150	162
Ultimate tensile strength (ksi)	187	199	206
Elongation (%)	28	25	28
Reduction in area (%)	23	21	24
Rockwell C hardness (HRC)	42	44	46

FIGURE 3

TYPICAL FATIGUE PROPERTIES OF CONVENTIONAL CAST/WROUGHT ALLOY 1 AND PM ALLOY 1

STRESS (KSI)	CAST/WROUGHT ALLOY 1	POWDER METALLURGY ALLOY 1
	# CYCLES IN MILLIONS	# CYCLES IN MILLIONS
120	14.6	10.3
125	7.1, 12.1	10.0
130	8.4*, 8.8*	10.2
135	0.01	4.3, 11.7
140	—	4.7, 15.7

**Point of fracture*

The fatigue results from this study are significantly higher than those found in previous tests to evaluate fatigue properties of annealed plus cold drawn Alloy 1 bar stock. The unannealed bar stock (both cast/wrought and PM) had significantly higher fatigue properties when compared with annealed and cold drawn Alloy 1 bar stock.

MICROSTRUCTURE

In the warm worked condition, the PM alloy has a slightly finer grain size than the conventionally produced alloy. The standard cast/wrought alloy has an ASTM grain size of 12.5 with an average grain dimension of 7.0 μ and an average grain area of 50 μ^2, as shown in Figure 4. The PM alloy has an ASTM grain size of 13.6 with an average grain dimension of 4.6 μ and an average grain area of 22 μ^2, as indicated in Figure 5.

> Both the higher tensile and fatigue strength capability of the PM alloy are attributed to the finer grain size and more uniform microstructure produced by the Micro-Melt powder metallurgy process.

FIGURE 4 — TYPICAL MICROSTRUCTURE OF CONVENTIONAL CAST/ WROUGHT ALLOY 1. WARM WORKED BAR STOCK, LONGITUDINAL SECTION, 1000X, ETCHANT HCL + H_2O_2 (3%).

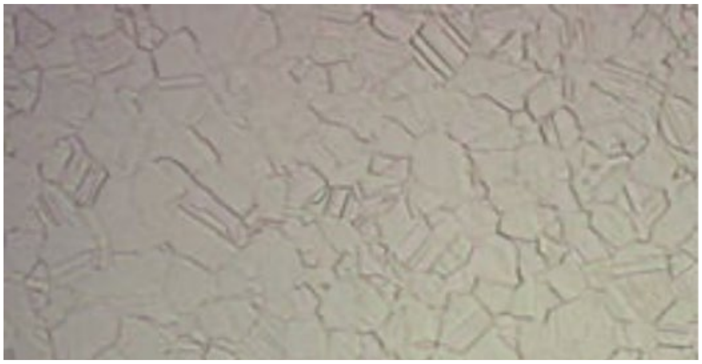


FIGURE 5 — TYPICAL MICROSTRUCTURE OF PM ALLOY 1. WARM WORKED BAR STOCK, LONGITUDINAL SECTION, 1000X, ETCHANT HCL + H_2O_2 (3%).

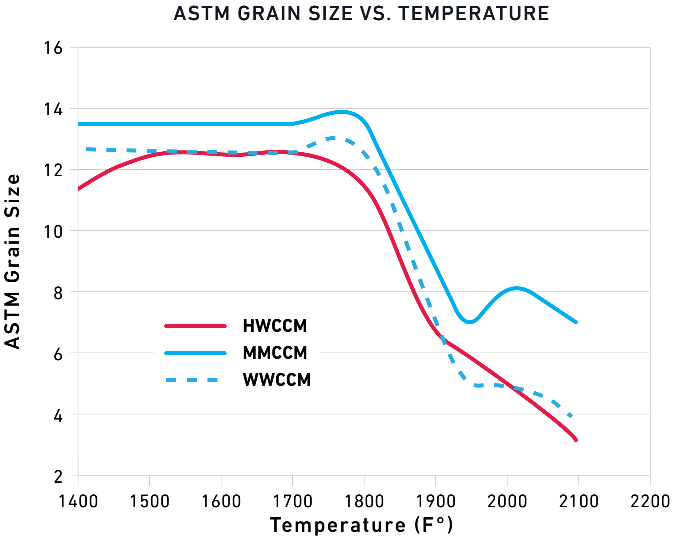
In further comparison, the conventionally produced hot worked alloy has an ASTM grain size of 11.5 with an average grain dimension of 8.7 μ.

THERMAL TREATMENTS

A study was conducted to evaluate the effects of various thermal treatments on the microstructure and hardness of the conventional alloy and the PM alloy. Samples of the conventional alloy were tested in the unannealed hot worked and unannealed warm worked condition. Samples of the unannealed warm worked PM alloy were also tested. The samples received 30 minute air-cool heat treatments using a temperature range from 1500°F (815°C) to 2100°F (1149°C).

Grain structure and hardness were evaluated on the as-received samples and after each heat treat cycle. Microstructure showed that the PM alloy exhibited a finer ASTM grain size in the as-received unannealed condition, and also maintained that finer grain structure after each heat treatment evaluated (Figure 6).

FIGURE 6 — EFFECT OF THERMAL TREATMENT ON ASTM GRAIN SIZE FOR THE PM ALLOY (MMCCM) AND CONVENTIONAL ALLOY 1.



Data developed from the evaluation clearly indicates that the powder-processed alloy maintains a consistently finer grain size than the cast/wrought alloy throughout the heat treatment range, especially after exposure to temperatures above 1900°F (1038°C).

The dramatic differences in grain size capability between the PM alloy and the cast/wrought alloy can be readily discerned in Figure 7, showing structure for the conventional cast/wrought alloy, and Figure 8, showing structure for the PM alloy.

FIGURE 7 — CONVENTIONAL CAST/WROUGHT ALLOY 1. WARM WORKED + 2100°F, LONGITUDINAL SECTION, 100X, ETCHANT HCL + H_2O_2 (3%), ASTM GRAIN SIZE 4.5, AVERAGE GRAIN AREA 11,000 µ².

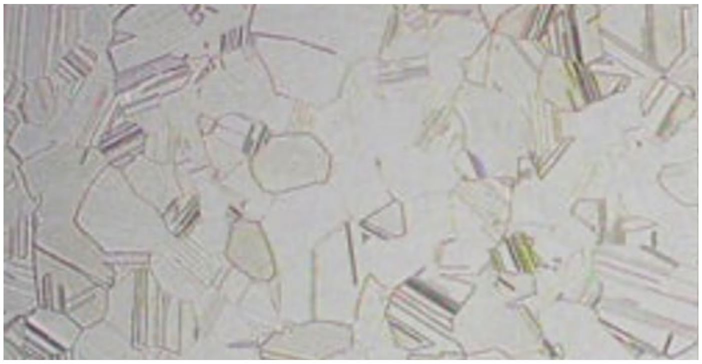
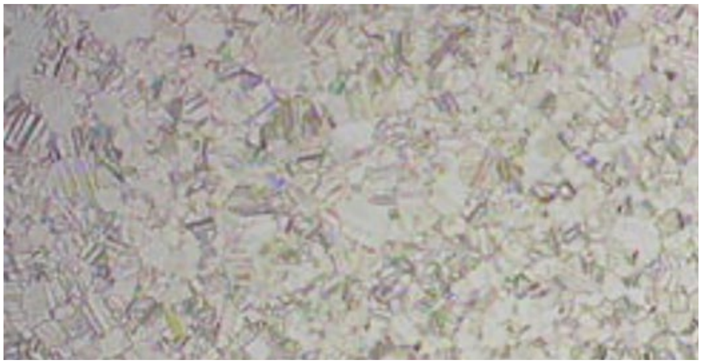


FIGURE 8 — PM ALLOY 1. WARM WORKED + 2100°F, LONGITUDINAL SECTION, 100X, ETCHANT HCL + H_2O_2 (3%), ASTM GRAIN SIZE 7.0, AVERAGE GRAIN AREA 2,000 µ².



Of particular interest is the grain size difference noted in Figures 7 and 8 after a 2100°F/30 minute cycle. This is a relatively common forging temperature used during the processing of orthopedic implants. After exposure to a temperature of 2100°F (1149°C), cast/wrought Alloy 1 developed a grain size of ASTM 4.5 with an average grain area of approximately 11,000 µ². In contrast, the Micro-Melt PM alloy developed an ASTM grain size of 7.0 with an average grain area of approximately 2,000 µ².

CARBIDE PRECIPITATE AND HARDNESS

Additional findings further emphasize the unique characteristics of the PM alloy. At 1900°F (1038°C), which is within the carbide precipitate range for the F1537 Alloy 1 tested, a significant difference was observed in the nature of the carbide precipitate between the cast/wrought alloy and the PM alloy. As can be seen in Figures 9 and 10, the cast/wrought alloy developed a banded carbide precipitate while the PM alloy tended to have more uniformly dispersed carbide precipitate.

> The PM process greatly decreases the likelihood for localized segregation and possible banding, which can occur in the cast/wrought alloy at times.

FIGURE 9 — CONVENTIONAL CAST/WROUGHT ALLOY 1. WARM WORKED + 1900°F, LONGITUDINAL SECTION, ETCHANT HCL + H_2O_2 (3%), CARBIDE PRECIPITATE BANDING.

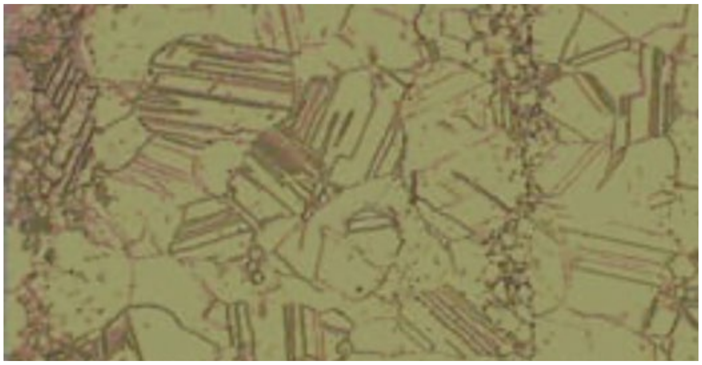
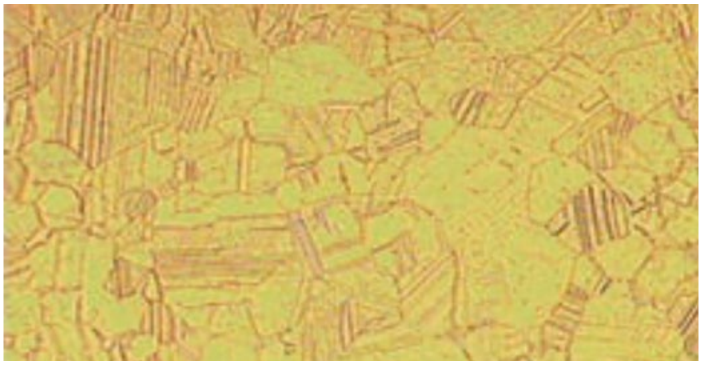
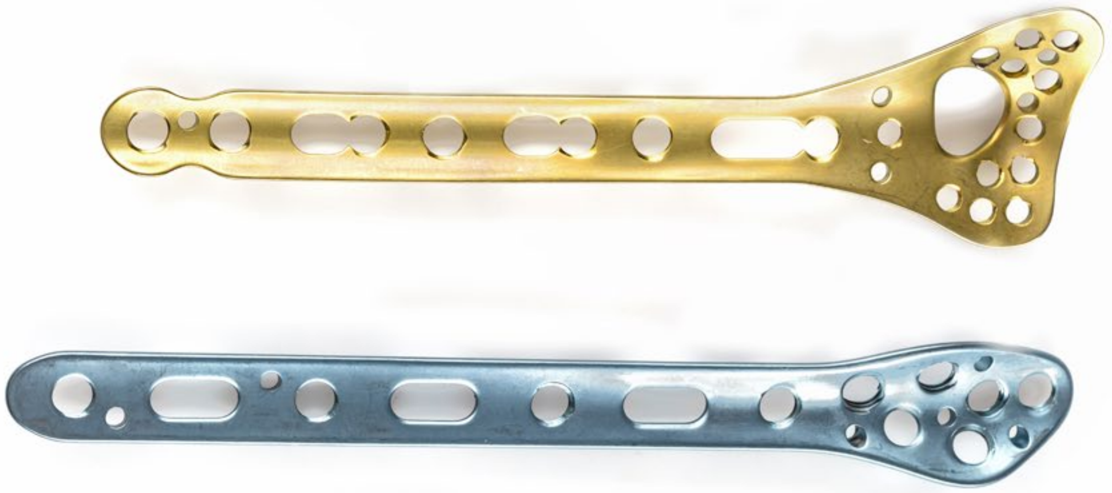


FIGURE 10 — PM ALLOY 1. WARM WORKED + 1900°F, LONGITUDINAL SECTION, 400X, ETCHANT HCL + H_2O_2 (3%), UNIFORM CARBIDE PRECIPITATE.

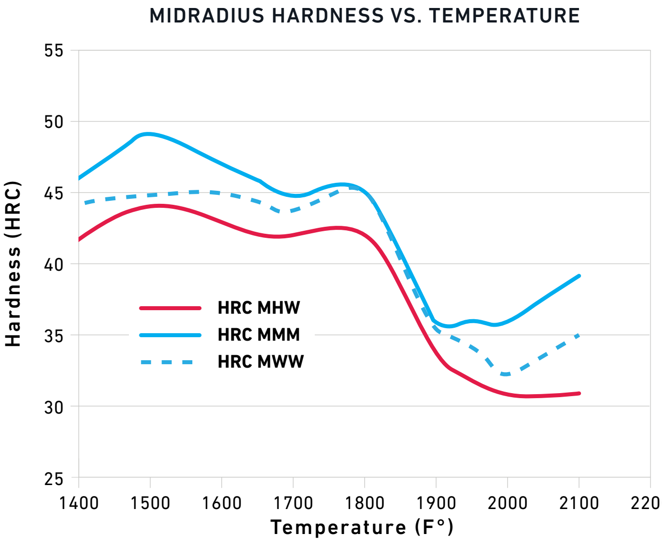




The precipitate in both the cast/wrought and PM material was completely solutioned at 1950°F (1066°C). Once solutioned, the carbide does not tend to re-precipitate if exposed again to temperatures in the 1600°F (871°C) to 1900°F (1038°C) range.

In addition to microstructure evaluations, surface-to-center hardness profiles were also completed on each sample in the as-received unannealed condition, and also after each heat treating cycle. The PM alloy had consistently higher hardness on the surface, at midradius (Figure 11) and the center in the as-received, unannealed condition as well as after each heat treating cycle, when compared with both the hot worked and warm worked cast/wrought alloy.

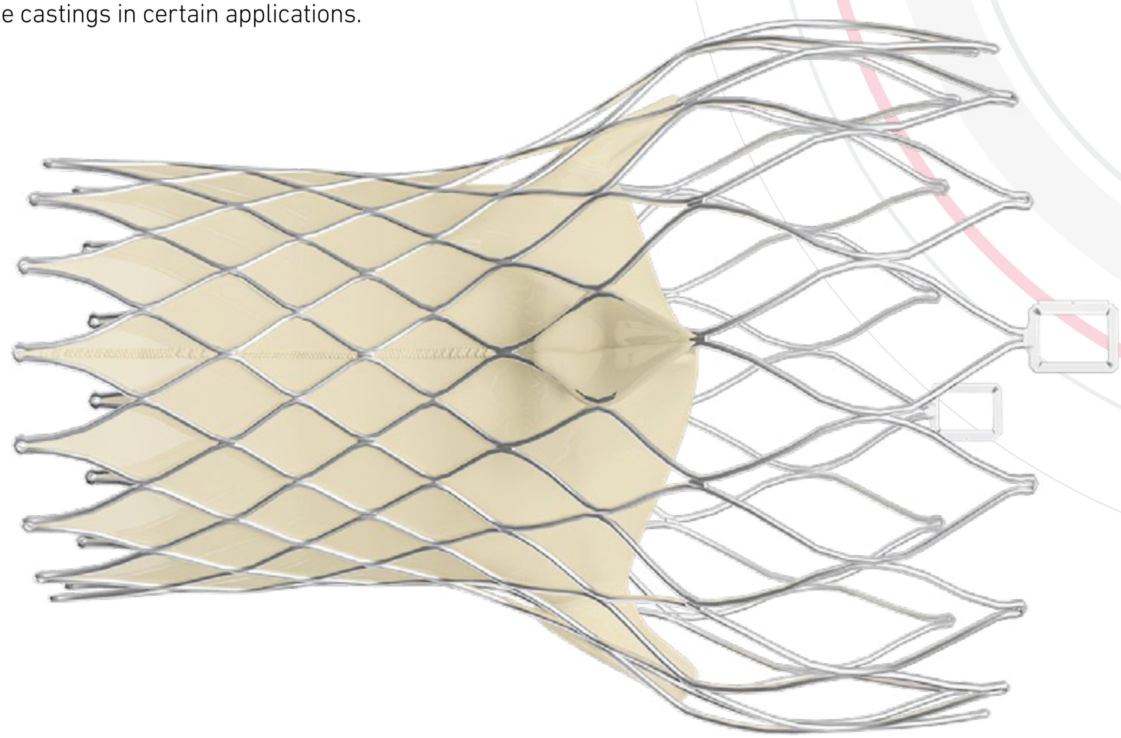
FIGURE 11 — MIDRADIUS HARDNESS PROFILE OF PM ALLOY 1 (HRC MMM) VS. HOT WORKED (HRC MHW) AND WARM WORKED (HRC MWW) CAST/W



CONCLUSION

The unique attributes developed by the Micro-Melt powder metallurgy process results in an Alloy 1 (BioDur CCM) F1537 bar material that exhibits higher strength, enhanced fatigue resistance, increased hardness, improved microstructural uniformity, and finer grain size in the unannealed condition as well as after exposure to elevated temperatures.

These benefits allow the material to be manufactured to smaller diameters without the need for cold working and annealing, which can be detrimental to grain size and, subsequently, fatigue strength. In addition to a smaller diameter, the alloy also lends itself to the manufacturing of special shapes that could replace castings in certain applications.



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