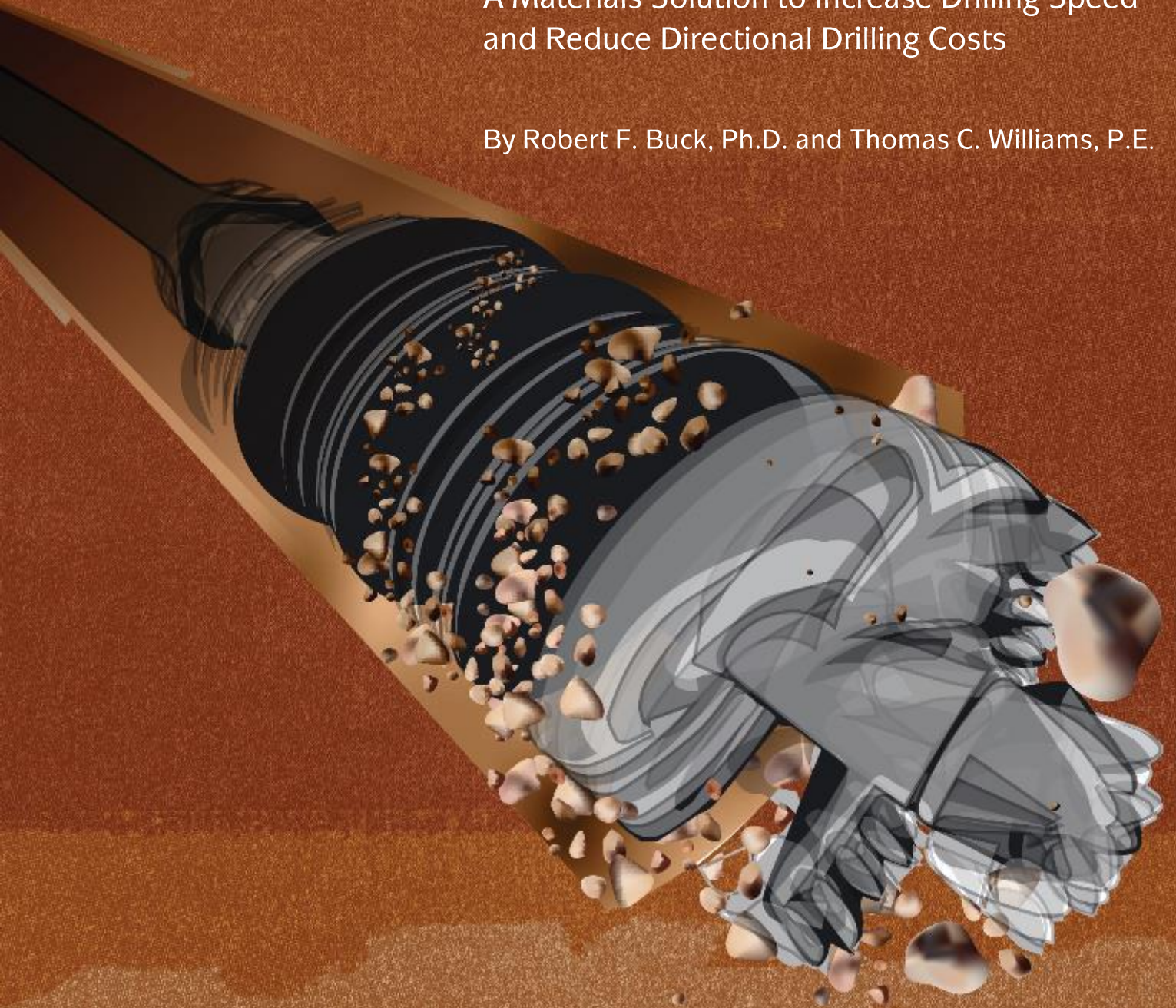




Performance Drilling

A Materials Solution to Increase Drilling Speed
and Reduce Directional Drilling Costs

By Robert F. Buck, Ph.D. and Thomas C. Williams, P.E.



Abstract

The widespread adoption of directional drilling, particularly horizontal drilling in unconventional reservoirs, has led to a period of increased oil supply. Land-based horizontal drilling, where operational efficiency is critical, now accounts for most activity, especially in the North American plays [1]. Directional drillers are pressured to drill as quickly as possible using one of several techniques, the most popular of which utilizes the positive displacement, or “mud”, motor [2]. Mud motors using conventional alloy steels for critical components are now operated at or above their design limits as drillers compete to finish wellbores in record time. Stronger, tougher materials can extend design limits to accommodate increased torque-at-bit and rates of penetration (ROP) without increasing tool size.

In response to industry demands, Carpenter Technology Corporation has introduced CarTech PremoMax® alloy (UNS K52260), a premium, re-melted, alloy steel that offers an attractive combination of high strength and toughness, excellent fatigue resistance, and good hardenability. Strength is typically improved by 20%, and toughness by 30% compared to re-melted 4330+V. CarTech PremoMax alloy has been used successfully as mandrels, driveshafts, adaptors and related mud motor components. Its use has allowed directional drillers to drill with greater confidence, extend mud motor life, and reduce total drilling cost.

An Introduction to Directional Drilling

Dramatic changes have occurred within the drilling industry since the early 2000s (Figure 1). In January 2003, the distribution of North American well trajectories was: 66% vertical, 7% horizontal, and 27% directional, (“directional” defined as an intentional deviation of less than 80° from the vertical [1], whereas “horizontal” generally involves an inclination of greater than 80° from the vertical). In April 2018, the distribution of wells being drilled was: 6% vertical, 88% horizontal, and 6% directional. The dramatic shift in well trajectories from vertical and directional to horizontal can be attributed to the rapid development and production of unconventional natural resources (the “shale revolution”).

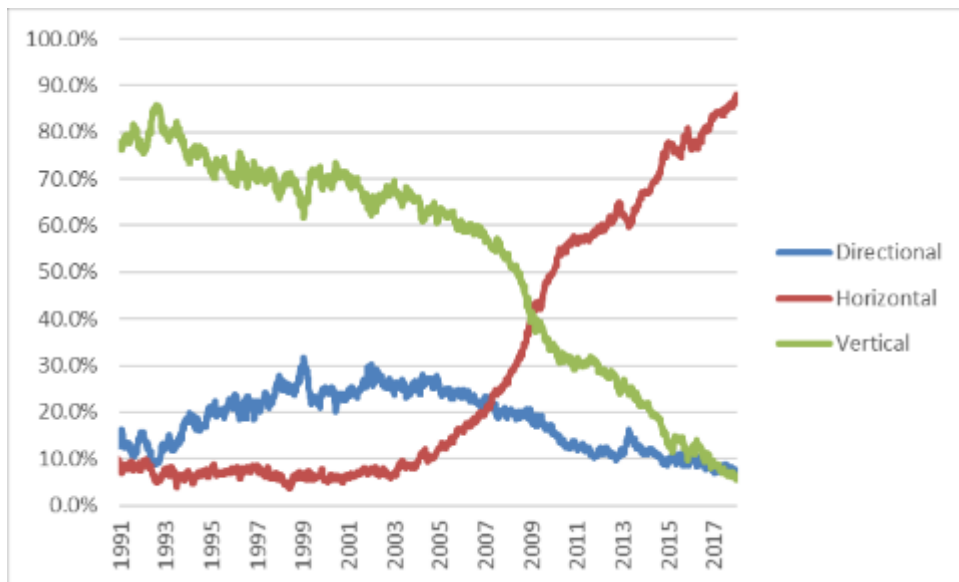


Figure 1: North American Rig Count by Trajectory [1]

Rotary steerable systems (RSS) have become the latest directional drilling technology, first commercialized in the 1990s. These tools permit precise guidance of drillstrings rotated at the surface by bottom hole assemblies that point and/or push the bit in the desired direction. The constant rotation of the entire drill string reduces drag, particularly in curves and horizontal well sections.

RSSs have steadily increased their presence in the horizontal drilling market since their introduction in the 1990s. However, PDMs maintain a dominant market share, estimated to be approximately 70%, primarily due to lower operating cost [2]. Nevertheless, RSSs do have several advantages over PDMs: increased ROP, smoother wellbores, and longer reach laterals. However, the advantages come with drawbacks, including increased day rates, higher lost-in-hole charges, and greater complexity. PDMs have the advantages of delivering more torque to the drill bit and drilling tighter curves. Hybrid systems exist where an RSS is assisted by an inline PDM to provide additional torque and rotation rate at the bit and reduce rig top drives power requirements [6]. Some operators choose to utilize both PDMs and RSSs on wells to capitalize on each systems' strengths.

Positive Displacement Motors

Although RSSs continue to grow in popularity, PDMs remain the predominant directional drilling method. A typical mud motor assembly is shown in Figure 3 and consists of a power section to convert hydraulic energy into rotational energy, a transmission to convert eccentric motion of the power section's rotor to axisymmetric rotation, and a bearing assembly just above the drill bit to handle thrust and radial loads. The transmission section's outer housing is sometimes bent by as much as 4° to drill directionally.

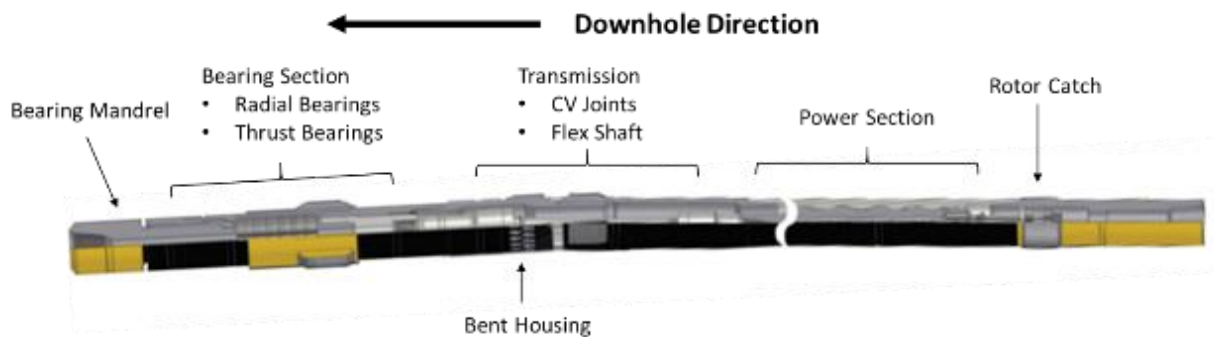


Figure 3: A Typical PDM (Mud Motor) Assembly Designed by Rival Downhole Tools (US Patent 10,041,299) [7]

PDMs are driven by the interaction of a lobed rotor and stator, each with helical profiles, in the motor's power section. The rotor has one fewer lobe than the stator to create a fluid-filled void that progresses down the length of the power section as the rotor nutates. Fluid pumped into the power section causes rotation. The rotor/stator lobe count affects the torque output and rotational speed of the motor. Generally, increasing the number of lobes increases torque and reduces revolution rate as shown in Figure 4. Torque and revolution rate are also affected by the number of helical revolutions of the rotor/stator, called stage count, and the pitches of the rotor and stator helices.

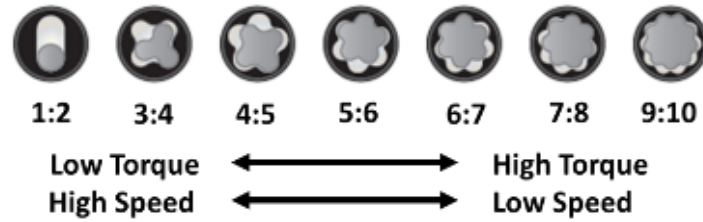


Figure 4: PDM Rotor/Stator Lobes

Stator sections had, until recently, been the limiting factor for motor performance. Typical stators are steel tubes with molded elastomers inside. The elastomers form a tight seal against the rotor and withstand the differential pressures required to drive the motor. The situation is further complicated by operating temperatures that can exceed 200°F (93°C) and drilling fluids that can attack elastomers and cause them to fail prematurely. Advances in elastomer technology and the use of even-walled stators, in which the stator's inner diameter is cut with the required helical pattern and an even layer of elastomer is overlaid for sealing, have increased stator performance. Cross-sections of conventional and even-walled stators are shown in Figure 5.

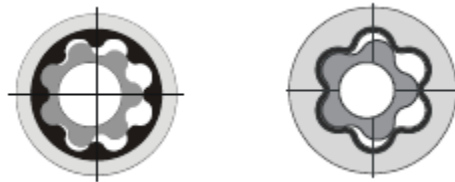


Figure 5: Conventional (L) and Even-Walled (R) Stator Cross-Sections

The rotor nutates eccentrically within the stator, necessitating a transmission to convert this motion into purely axisymmetric rotation. The transmission also transmits power through the bent housing on motors used for directional drilling. The two most common transmission types are constant-velocity (CV) joints and flexible drive shafts (flex shafts). Flex shafts are threaded directly onto the rotor and bearing mandrel and are stressed in bending and torsion as the motor turns. CV joints are multi-part assemblies consisting of a drive shaft with bearing adaptors at each end. These adaptors engage the ends of the CV drive shaft such that they transmit torque without bending stress. This is usually accomplished by ball bearings that engage pockets in the drive shafts and adaptors. Alternative engagement profiles including interlocking fingers, inserts, hexagonal profiles, and other methods accomplish the same function. A typical CV assembly is shown in Figure 6.

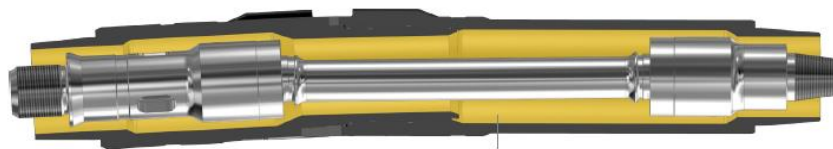


Figure 6: PDM Constant Velocity Joint from Rival Downhole Tools (US Patent 10,041,299) [7]

The final component of the motor drivetrain is the bearing mandrel, which connects the transmission to the drill bit. The bearing mandrel engages thrust and radial bearings near the bottom of the motor to transmit axial and side loads from the bit to the drill string. The structural integrity of these mandrels is critical, as a failure could result in a drill bit being left downhole. Since the diamond cutters used in drill bits cannot be milled out, this situation requires the well to be side-tracked to avoid the lost bit, or abandoned completely.

Most components in drivetrains are alloy steels. The standard materials used for CV adaptors, CV shafts, and bearing mandrels have been chrome-molybdenum-nickel steels like AISI 4330+V. High-strength stainless steels like CarTech Custom 465® alloy are used when additional corrosion resistance is desired. Flex shaft transmissions are made from titanium, due to its low Young’s modulus and good corrosion resistance, or high-strength alloy or stainless steels. Materials used in mud motors should be strong, tough, and fatigue resistant. They must also be compatible with a variety of surface coatings including: tungsten carbide overlays, nitriding, carburizing, and/or laser surface hardening.

Challenges in Directional Drilling – A New Paradigm

Economic, land-based, horizontal drilling has been a driving force for unconventional resource development in shale plays globally. The rapid development of unconventional resources unlocked vast reserves, but had an unexpected consequence: the oil price collapse of 2014. By early 2016 the industry was contending with prices nearly one third of those at the 2014 peak. Directional drillers were tasked with slashing the time needed to drill a well without causing tool failures. Day rates for the rig and rental services dropped and competition for jobs intensified, so the consequences of tool failures became financially ruinous. Drillers using RSSs and PDMs pushed tools to their limits to increase ROP. The cost-effectiveness and ubiquity of PDMs among a wide base of directional drillers made their improvement an industry focus.

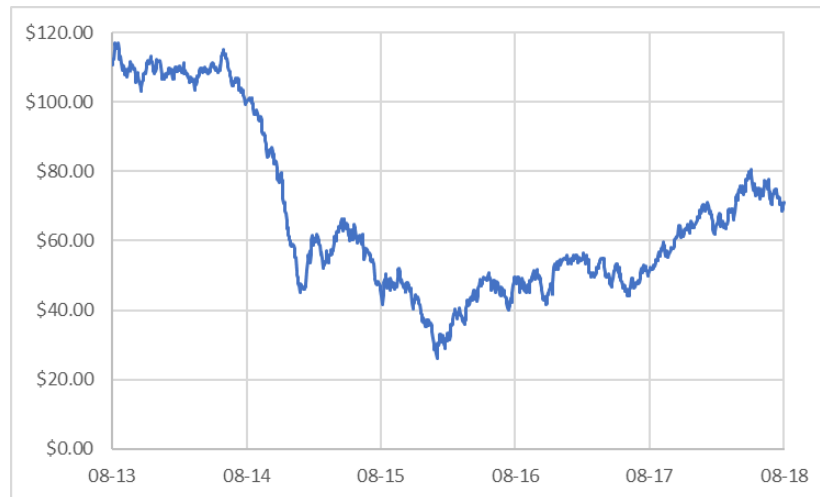


Figure 7: 5-Year Brent Crude Price (August 2013 to August 2018)

Increasing Rate of Penetration with PDMs

Improved power sections, aided by the introduction of better elastomers like hydrogenated acrylonitrile butadiene rubber (HNBR), even-walled stators, and more powerful mud pumps on rigs, allowed drillers to cut the time to drill shale wells from 20 days to five or fewer [8]. Operators in the Permian Basin doubled the lateral footage drilled on a per-rig basis between 2014 and 2016 [9].

The result of technology advances and economic pressure has been an increase in at-bit torque and fluid flow rates without an accompanying increase in tool size. In 6.75-inch motors, the torque output from power sections has increased from around 12,000 ft-lbs to more than 24,000 ft-lbs and designers have plans for more than 40,000 ft-lbs. Such torque increases also require higher flow rates to drive the power section, cool the motor, and carry cuttings away from the bit, placing additional demands on motor components. The geometry of the tool is constrained by hole size, so advancements in both mechanical designs and materials are required to reach these targets.

CarTech PremoMax Alloy – A Materials Solution for PDM Drivetrains

Carpenter Technology developed CarTech PremoMax alloy to address the limitations of alloy 4330+V in today's challenging drilling environments and improve the performance and life of PDM drivetrains. While alloy 4330+V is the most popular alloy steel used today for mud motor shafts and related components, the higher torque output required by PDM drivetrains has pushed components beyond design limits and led to higher failure rates. CarTech PremoMax alloy can offer on average a 20% improvement in minimum yield strength and 30% improvement in impact toughness, resulting in extended mud motor life and reduced total drilling cost.

CarTech PremoMax alloy (UNS K52260) is vacuum-arc re-melted (VAR) for superior cleanliness and employs a simple heat treatment of water or oil quenching and tempering. Its unique chemistry not only creates improved yield strength and impact toughness, but field testing has also shown that it gets slightly stronger and tougher after long-term exposure at elevated temperatures. Additionally, it exhibits high fracture toughness and galling resistance, high fatigue resistance, good hardenability and can be surface hardened using various techniques.

The unique characteristics and mechanical properties of CarTech PremoMax alloy are presented in the following sections. For supporting information, download the [alloy fact sheet](#) at cartech.com.

Chemistry Comparison

CarTech PremoMax alloy has a unique chemistry (Table 1), containing lower carbon, molybdenum, and nickel than 4330+V, but higher manganese, silicon, chromium, and vanadium. It also contains copper, which is absent in 4330+V. The modest carbon content of CarTech PremoMax alloy enables water quenching without cracking. The unique mix of elements results in the superior properties of CarTech PremoMax alloy after proper processing.

Table 1: Chemistry comparison of CarTech PremoMax and 4330+V

Alloy	C	Mn	Si	Cr	Ni	Mo	V	Cu
CarTech PremoMax®	0.22	2.00	0.90	2.10	0.70	0.20	0.35	0.50
4330+V	0.30	0.75	0.30	0.85	1.80	0.40	0.07	-

Heat Treatment and Room Temperatures Mechanical Properties

CarTech PremoMax alloy is typically austenitized between 1600°F (871°C) and 1750°F (954°C), water or oil quenched, and tempered between 450°F (232°C) and 550°F (288°C). No cryogenic treatment is needed. To avoid embrittlement, CarTech PremoMax alloy should not be held for any appreciable amount of time between 600°F (316°C) and 1100°F (593°C). As such, CarTech PremoMax alloy should not be nitrided using conventional techniques.

Yield strengths for 4330+V ranged from 155 to 167 ksi, while ultimate tensile strength (UTS) values were 171 to 180 ksi. CarTech PremoMax alloy yield strengths, per ASTM A370, were 180 to 192 ksi (25 ksi higher), and UTS values were 221 to 234 ksi (50 ksi higher). Noteworthy, is that the yield strength of CarTech PremoMax alloy is greater than the ultimate tensile strength of 4330+V, resulting in failure of 4330+V before CarTech PremoMax alloy plastically deforms. Also remarkable is that the higher CarTech PremoMax alloy yield and ultimate tensile strengths are accompanied by an *increase* in impact toughness vs. 4330+V of about 30%.

Typical Charpy V-notch impact toughness (CVN), yield strength, and ultimate tensile strength of CarTech PremoMax alloy, are shown in Figure 8 and compared to 4330+V. All tensile and impact data in Figure 8 were generated from longitudinal, mid-radius samples taken from heat treated bars ranging in diameter from 2 inches to 8 inches.

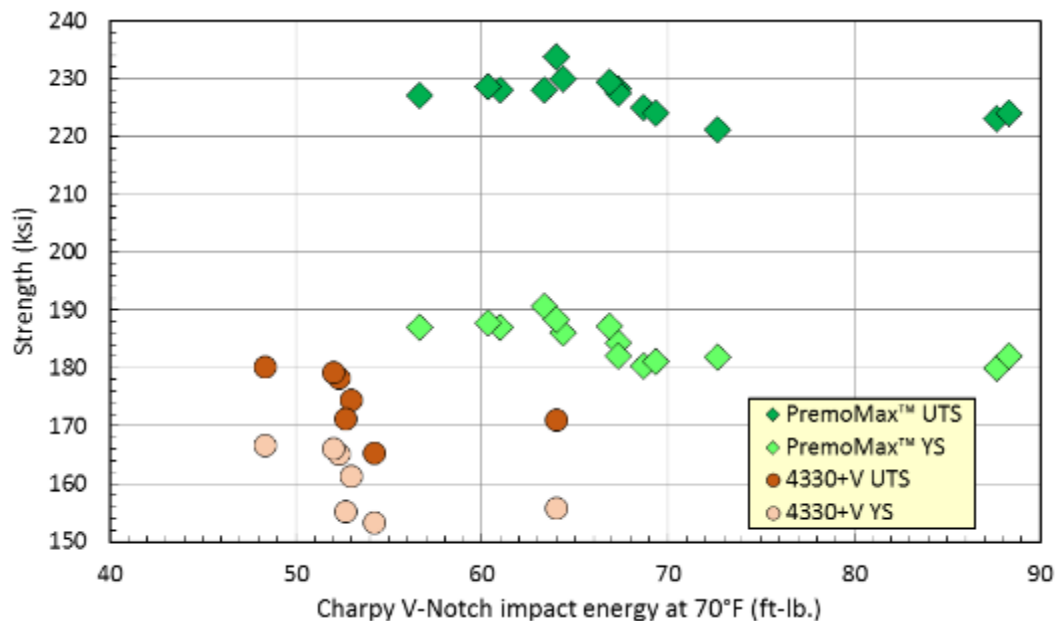


Figure 8: Yield strength and UTS vs. toughness of CarTech PremoMax and 4330+V ($2" \leq \phi \leq 8"$, longitudinal, mid-radius)

Scanning electron microscopy analysis of the fracture surface of a CarTech PremoMax alloy CVN sample revealed that fracture occurred, in part, by micro-void coalescence and dimpled fracture rather than the more typical quasi-cleavage fracture mode (Figure 9). Micro-void coalescence during fracture contributes significantly to the high impact toughness of CarTech PremoMax alloy.

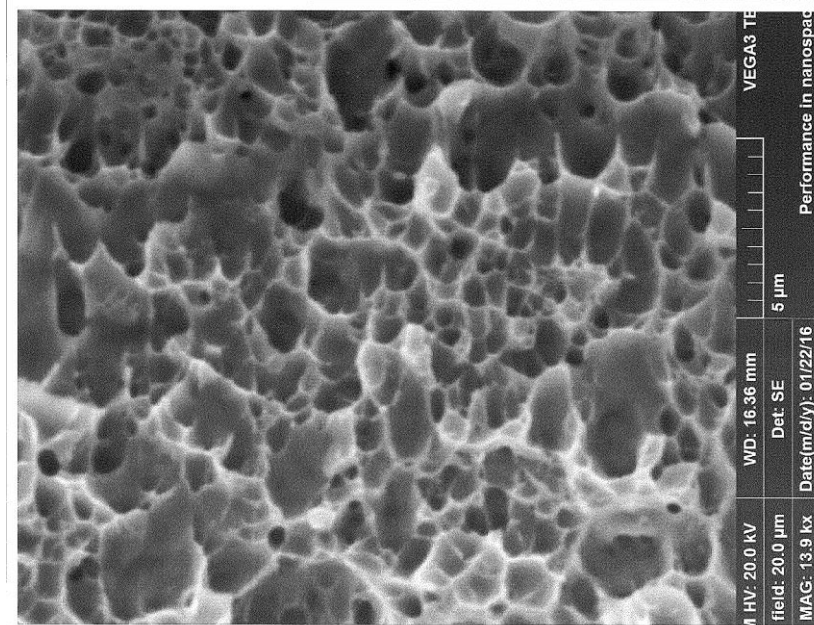


Figure 9: Micro-void coalescence on the fracture surface of a CVN CarTech PremoMax alloy sample

Effects of Long-Term Exposure at Elevated Temperature

The effect of elevated temperature exposure at 300°F (149°C) for up to 1,000 hours on the room-temperature yield strength and impact toughness of CarTech PremoMax alloy bar is shown in Figure 10. This data suggests that when CarTech PremoMax alloy is exposed to 300°F for up to 1,000 hours, the alloy gets stronger and tougher. The material does not show deterioration of properties at a bottomhole temperature of 300 °F, as toughness increases with time in service.

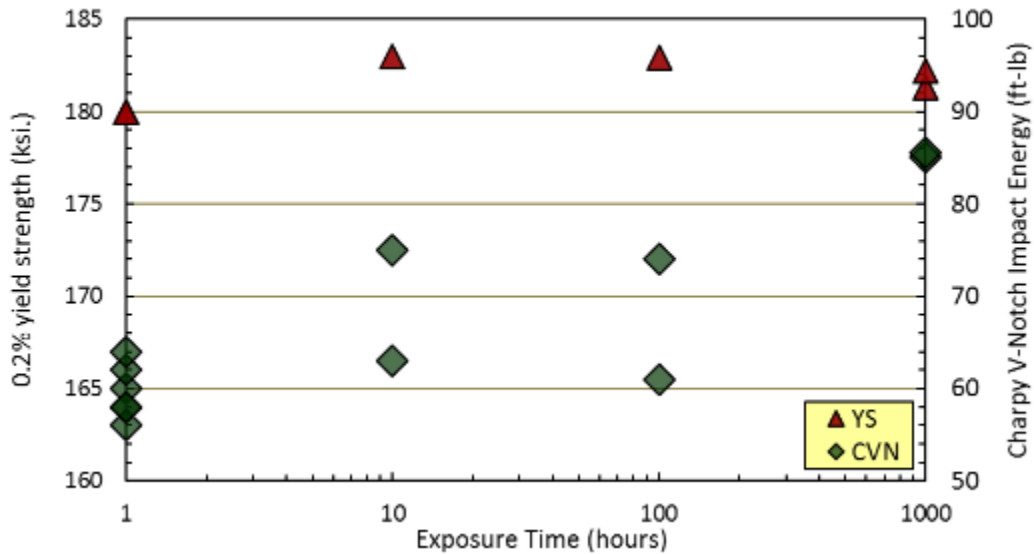


Figure 10: Effect of 300°F exposure on room temperature strength and impact toughness.

Charpy V-Notch Impact Properties

The effect of temperature on Charpy V-notch impact toughness is shown in Figure 11. The impact toughness in the longitudinal orientation is generally greater than the transverse orientation, as expected. In both the longitudinal and transverse orientations, the impact toughness of CarTech PremoMax alloy in the quenched-and-tempered condition decreases with temperature, but does not drop precipitously as is common in many carbon and alloy steels. CarTech PremoMax alloy does not exhibit a ductile-to-brittle transition in either orientation, making it well-suited for use in cold climates.

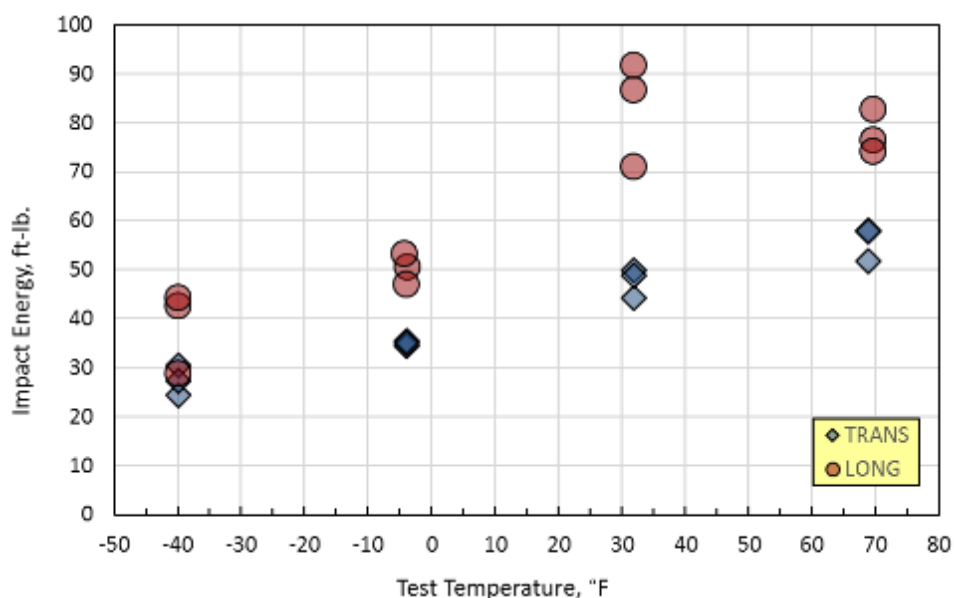


Figure 112: Effect of test temperature on the Charpy V-notch impact energy.

High Cycle Fatigue Properties

Rotating bending (R.R. Moore type) tests were conducted on quenched and tempered CarTech PremoMax alloy bar to determine its high-cycle fatigue resistance. Samples were machined and polished using standard industry specimen preparation techniques. Results are shown in Table 2; all tests were done with $R = -1$. The data suggest that the endurance limit (applied stress in which fatigue failure does not occur in less than 10 million cycles) for CarTech PremoMax alloy is approximately 120 ksi, or about 53% of the ultimate tensile strength. The 30 million cycle endurance limit is estimated to be 100 ksi.

Table 2: High cycle fatigue results of CarTech PremoMax bar. R = -1

Stress (ksi.)	No. of Cycles	Result
100	30,287,000	no failure
100	30,007,699	no failure
120	10,180,559	no failure
120	10,408,000	no failure
130	3,712,476	failure
140	77,932	failure
140	82,000	failure

Fracture Toughness and Galling Resistance

Fracture toughness (K_{IC}) samples were cut from quenched-and-tempered 7.20-inch round CarTech PremoMax bar. Samples having both R-L (longitudinal) and L-R (transverse) orientations were cut from a 7.20" RD commercial bar. The fracture toughness test results were invalid due to failure to achieve plane strain conditions. The sample was not large enough to satisfy the plane strain requirement. As such, only K_Q values were determined and were at or above 153 ksi $\sqrt{\text{in}}$ (167 MPa $\sqrt{\text{m}}$). Very few other alloys, like CarTech Aermet® 100 alloy, can offer such high UTS and fracture toughness properties as CarTech PremoMax alloy. This data suggests that CarTech PremoMax alloy is highly resistant to crack propagation.

CarTech PremoMax alloy galling resistance was determined per ASTM G98 (pin-on-block). To investigate the most conservative case, CarTech PremoMax alloy was used as both pin and block material. Results indicated that the threshold stress for galling to occur in CarTech PremoMax-on-CarTech PremoMax alloy conditions is 17.5 ksi (121 MPa).

Surface Hardening

The ability to combine a hardened case layer for wear resistance with a tough, strong core to absorb drilling shock loads is a unique attribute of CarTech PremoMax alloy. Even without intentional hardening, the as-quenched-and-tempered surface hardness of 48 HRC is a considerable increase over 4330+V, which is typically about 35 HRC.

The surface hardness of CarTech PremoMax alloy can also be increased using techniques such as carburizing, high velocity oxy-fuel (HVOF), laser hardening, laser cladding, and plasma transferred arc. Conventional nitriding techniques are NOT recommended for CarTech PremoMax alloy because of embrittlement that occurs if the material is exposed to typical nitriding temperatures. However, carburizing can be used as a substitute with great effectiveness.

A typical hardness profile after conventional gas carburizing is shown in Figure 12. Peak hardness exceeded 62 Rc with a case depth of approximately 0.080" (2 mm). Typical core properties after carburization are: 182 ksi. yield strength, 225 ksi. UTS, 13% elongation, 45% RA, and 55 ft-lb CVN impact energy at room temperature.

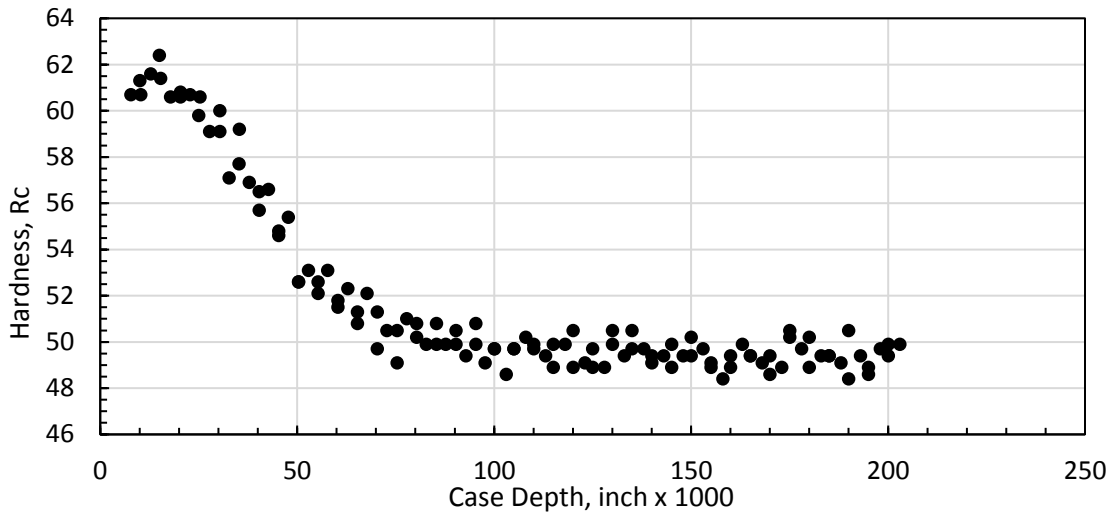


Figure 123: Microhardness profile after gas carburizing, austenitizing, oil quenching, cryogenic treatment and double tempering. Gas carburizing was done at 1700F for 7 hours and a carbon potential of 1%.

Case Study – Deformation of Bearing Races on PDM Mandrels

A major oilfield service company was experiencing deformation failure of its 4330+V bearing races on PDM mandrels. The severity of the deformation was detrimental to bearing life and required continuous rework machining when a lip formed, prematurely shortening the expected life of the part and creating higher maintenance expenses. To ensure they could meet the customer’s needs, multiple mandrels were kept in reserve in case replacement was needed during a drilling campaign, driving up the CAPEX cost and reducing rental revenue.

Carpenter Technology was consulted to provide a stronger, tougher alloy that could better withstand the demands of the drilling conditions. Carpenter’s field and metallurgy experts identified CarTech PremoMax alloy as a possible solution for the application due to its unique combination of properties that combined a harder case layer for wear resistance with a tough, strong core to absorb drilling shock loads.

Through ongoing field studies, the customer has reported that CarTech PremoMax alloy not only exceeds tensile strength and impact toughness of 4330+V, but it can withstand higher torsional loads by nearly 40%. While individual results are subject to variations of tool design, use, and drilling conditions, in this case, CarTech PremoMax alloy has extended the average mandrel life three to four times that of typical mandrels made with the 4330+V alloy while continuing to run in service. Figure 13 demonstrates the difference between the 4330+V alloy and the CarTech PremoMax alloy: the mandrel made with CarTech PremoMax alloy does not show the plastic deformation seen with 4330+V alloy after use in similar field conditions.



Figure 13: Bearing surface deformation on a 4330+V part (L) is significantly improved with CarTech PremoMax alloy (R).

These results translate into faster and more efficient drilling, with fewer disruptions from tool failure and downtime, contributing to a reduction in Capital Cost and overall operating costs. As a result, the company has specified CarTech PremoMax alloy for use in this application.

"To improve the torque capabilities, [tool components] can now be machined out of PremoMax. PremoMax has excellent mechanical properties, with a higher ultimate tensile strength than the current alloy steel materials. With an upgrade in material properties, the new PremoMax [tool components] will be able to withstand higher torsional loads during drilling operations."

CarTech PremoMax alloy's advantages in surface hardness and yield strength were leveraged to solve the surface deformation issues. Additionally, CarTech PremoMax alloy outperforms other competitive alloys on torque handling by 40%. CarTech PremoMax alloy allowed the equipment manufacturer to increase the service life of the mandrel, which reduced CAPEX, maintenance, and spare part requirements, providing higher unit availability that ultimately benefited the E&P company with a lower total cost to drill the well and reduced non-productive time (NPT).

Conclusions

CarTech PremoMax alloy, specifically designed to address PDM challenges, has proven to be a robust material during field trials in PDM driveline components and has extended component service life in some cases by three to four times above what is possible with 4330+V alloy.

With horizontal and directional drilling in shale formations accounting for 94% of the North American drilling market in 2018, PDMs have become the predominant drilling technology in the market for cost savings and availability. But, improved motor power sections and increased torque outputs have pushed drill string components to their limit in the quest to increase ROP.

CarTech PremoMax alloy demonstrates that material improvements can provide new solutions to motor design challenges made difficult by size limitations of standard hole sizes. The alloy possesses the requisite mechanical properties to enable designers to adapt to more demanding downhole conditions, reduce the consequences of failure and improve drilling productivity.

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