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An ADI Crankshaft Designed for High Performance in TVR's Tuscan Speed Six Sports Car

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ABSTRACT

The TVR Tuscan Speed Six, (produced by TVR Engineering in Blackpool, England) is a high performance automobile, by any measure. This low volume sports car weighs 1,100 kg (2,420 lbs) and is powered by a 4-litre in-line six-cylinder engine that develops over 350 bhp and 310 ft-lb of torque. TVR Engineering selected an Austempered Ductile Iron (ADI) crankshaft for its combination of low cost, low weight and high torsional strength. Not since Ford dabbled with ADI in its race cars in the 1980's has a manufacturer chosen ADI for its crankshafts. Although virtually all the major automotive producers and the Motor Industries Research Association (MIRA) have investigated ADI for use in crankshafts, this is the only known production application of ADI crankshafts in automobiles.

ADI presents a useful set of properties for the design engineer. With ever increasing specific power requirements for new engine designs, new material/process combinations for engine components are being explored. This paper will discuss the properties of ADI, the reason for its selection for this crankshaft, and its suitability for this application.

INTRODUCTION

TVR Engineering is a company founded on a design heritage with racing pride. The company was conceived in 1947 when Trevor Wilkinson developed his first sports car. Over time, the TVR name has become synonymous with power, agility, and style. Being a low-volume manufacturer gives TVR the ability to experiment with different material and process combinations that would be too cumbersome for a larger company. This allows greater flexibility in design and manufacture which permits them to try unique options. This gives TVR a competitive advantage in the automotive market.

Figure 1- TVR Tuscan Speed Six, ghosted hood view.

ADI Treatments, Ltd. (Birmingham, England) is a licensee of Applied Process, Inc., (AP). This company and its affiliates specialize in the Austempering process, an isothermal heat treatment known to produce improved properties in cast irons. TVR and AP joined forces to produce the Austempered Ductile Iron crankshaft used in the Tuscan Speed Six engine.

THE TVR TUSCAN SPEED SIX

Anyone who has been fortunate enough to drive the Tuscan Speed Six would know; this car has style, control and power! The Tuscan Speed Six debuted in 1999 for sale in the UK and Japan as a right-hand-drive-only vehicle. Looking at the striking styling of this sports car, one would never believe it was intended to be an every day vehicle – but to drive it, one can see that this car delivers performance while being easy to handle.

THE CAR – The Tuscan Speed Six, a two-seater with a targa style roof, combines aerodynamic styling with a high power-to-weight ratio that gives it remarkable performance. By using composite materials, TVR created curves in the body that could not be accomplished with regular steel stampings. Inside and out, simplicity was the key to its unique style. The Speed Six delivers excellent handling, performance, and speed. As a rear-wheel-drive with a 5-speed manual transmission, the Speed Six accelerates from 0-96.5 km/h (0-60 mph) in 4.2 seconds. With a top speed of 289.6 km/h (180 mph), it accelerates from 0-190.6 km/h (0-100 mph) in 9.6 seconds.

Figure 2- Tuscan Speed Six

THE POWERTRAIN – The Speed Six is equipped with an in-line six-cylinder engine with 4 valves per cylinder. The engine has a displacement of 3996 cm^3 (243.8 in^3), with a bore and stroke of 96 mm x 92 mm (3.77 in x 3.62 in). The maximum torque output is 420.3 Nm (310 ft/lbs) at 5250 rpm. The engine is constructed of an aluminum alloy with cast iron dry liners. There are two engine configurations available: one with 350 bhp output at 7000 rpm, and the other at 375 bhp output at 7500 rpm. The 350 bhp engine uses an ADI crankshaft cast and machined by TVR and heat-treated by ADI Treatments, Ltd.

Figure 3- Tuscan Speed Six view under the hood

THE CRANKSHAFT – Forged steel seen in **Figure 4**, was the original material of choice for the crankshaft in this inline 6-cylinder engine. Due to the high cost to manufacture, steel was eliminated as material consideration for this design.

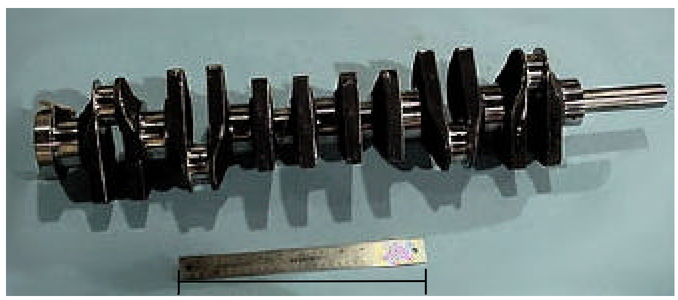
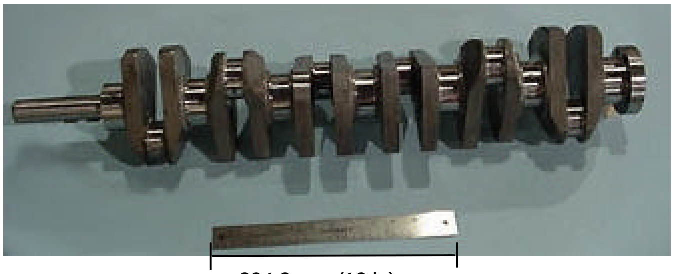


Figure 4 - Steel crankshaft for the Tuscan Speed Six – 34 kg (75 lbs.)

TVR designed and tested a crankshaft made from 800/2 ductile iron (also known as spheroidal graphite iron or SG iron) as pictured in **Figure 5**. However, during testing at TVR on a bench dynamometer and in vehicles, this crankshaft failed in some cases with a fatigue crack at a fillet radius on the flywheel end of the crankshaft.



304.8 mm (12 in)

Figure 5 - Ductile Iron crankshaft for the Tuscan Speed Six – 29.9 kg (66 lbs.)

ADI (**Figure 6**) became the obvious next choice, as TVR was already using this material for the crankshaft in their V8 engines. However, there were initial reservations about distortion in the manufacture of the crankshaft. In order to compensate for distortion in the design phase, the crankshaft was rough machined, heat-treated and then finish machined. This significantly reduced distortion as a concern, and the finish machining after heat treatment gave the crank the added benefit of higher strength. The ADI crankshaft out-performed the ductile iron version, showing no signs of fatigue cracking during bench testing. ADI's internal dampening characteristics also gave the engine superior noise properties compared to engines with steel or ductile iron crankshafts.

304.8 mm (12 in)

Figure 6 - ADI crankshaft for the Tuscan Speed Six – 29.5 kg (65 lbs.)

TESTING

TVR used a bench dynamometer, like the one shown in **Figure 7**, to rigorously test the engines. The ductile iron crankshaft was run in this configuration at 6000 RPM. This created a high torsional load, and failures occurred after 1 hour of testing. The ADI crankshaft was tested in the same configuration and showed no signs of fatigue cracking after 4 hours at 6000 RPM. Road testing followed successful dynamometer testing. The ADI crankshaft experienced no failures during road testing.

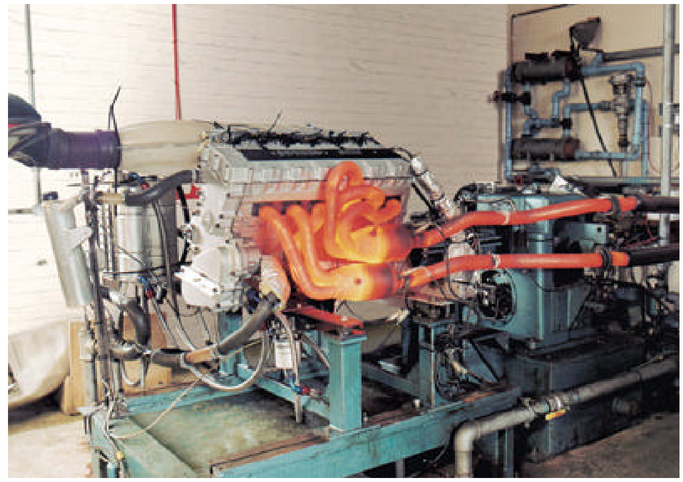


Figure 7- Tuscan Speed Six engine undergoing dynamometer testing at TVR Engineering, Ltd.

Tensile, impact and rotating bending fatigue test bars were machined from steel, ductile iron and ADI crankshafts in order to compare their mechanical properties. The results are listed in Table 1. Fatigue curves (stress versus cycles to failure) for each material are given in **Figure 8**. It is evident from **Figure 8** that the steel and ADI crankshafts outperform the ductile iron

Table 1 - Test results for the Steel, Ductile Iron and ADI crankshafts, and the ASTM 897M-90 and ASTM 897-90 Standard ADI Grade 1 Specifications

	Steel	**Ductile Iron**	**ADI**	**ASTM ADI Grade 1**
Yield Strength MPa (KSI)	738 (107)	538 (78)	827 (120)	550 (80)
Tensile Strength MPa (KSI)	910 (132)	903 (131)	1083 (157)	850 (125)
Fatigue Strength MPa (KSI)	400 (58)	324 (47)	427 (62)	N/A
Impact Energy Joules (ft – lbs)	325 (240)	75 (55)	141 (104)	100 (75)
Elong. (%)	23.2	10.8	13.7	10
Hardness BHN	226-266	262-277	300	269-321

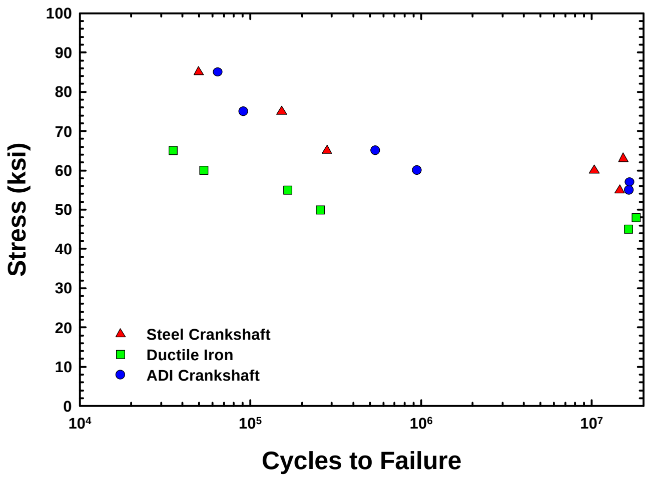


Figure 8 –Rotating Bending Fatigue Test results: Cycles to Failure vs. Stress. Data points at 10^7 cycles are runouts or the test specimens did not fail.

crankshaft. This result was expected, especially since the ductile iron crankshafts failed during preliminary testing.

The microstructures of each crankshaft were examined and are shown in **Figures 9 – 11**. The microstructure of the steel crankshaft in **Figure 9** is fine pearlite. The ductile iron crankshaft shown in **Figure 10** is predominantly pearlitic while the ADI microstructure in **Figure 11** is ausferrite.

SELECTING ADI

ADI was chosen over steel and ductile iron for this crankshaft application. However, the process did not start with ADI as the selected material. Ductile iron and steel were the original design choices.

STEEL - Steel's high fatigue strength and stiffness would appear to make it a desirable material to withstand the demands of this high performance engine. However, TVR was looking for high performance from their vehicle, but also low weight and affordability. They had the option of using steel, which could be machined from a solid billet, or forged. Machining a steel crankshaft from solid steel is time consuming and expensive. Manufacturing this part as a forging requires the use of expensive equipment. TVR's forged steel crankshaft weighs 4.5 kg (10 lbs.) more than the ADI crankshaft. The high weight and expensive manufacturing processes caused the steel crankshaft to be eliminated as the material for this application. Work previously done by Kovacs found that ADI could compete with forged steel in a crankshaft application in both strength and hardness as shown in **Table 2**.

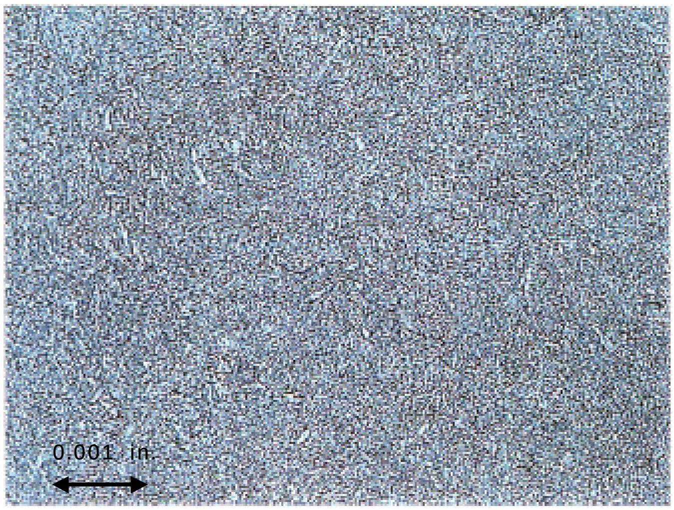


Figure 9 – Steel Crankshaft microstructure

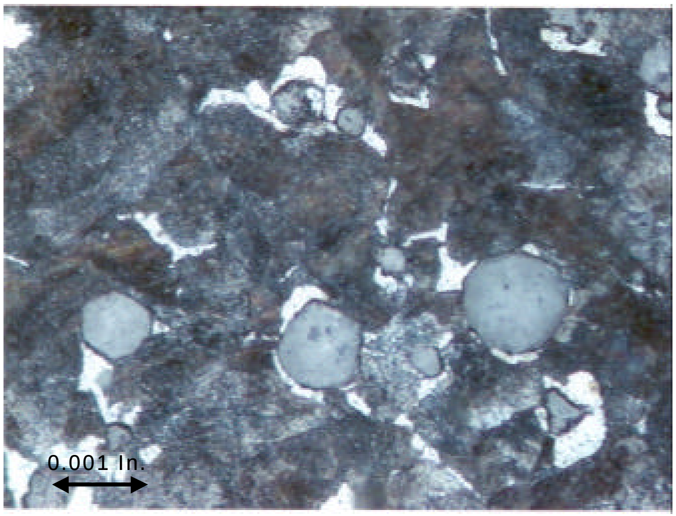


Figure 10 - Ductile Iron microstructure

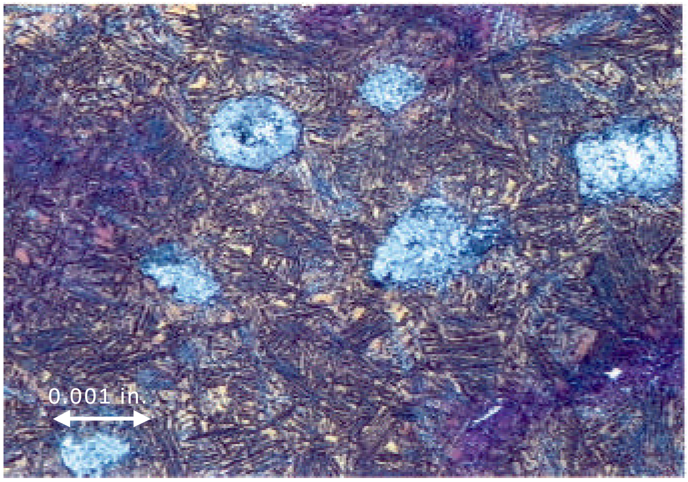


Figure 11 – ADI Crankshaft microstructure

Table 2 - Properties of Steel vs. ADI[2]

	Forged Steel	ADI
Yield Strength, MPa (KSI)	510.2 (74)	792.8 (115)
Tensile Strength, MPa (KSI)	779.1 (113)	1034.2 (150)
Modulus, GPa (MSI)	205.4 (29.8)	166.8 (24.2)
Elongation, %	10	9
Hardness, BHN	262	280

DUCTILE IRON - Ductile iron was chosen for an initial design for this engine. Ductile iron is easier to manufacture, and can be cast with more dimensional precision than steel, making it more cost effective. It is 10% less dense than steel, leading to lower weight for a given shape. Ductile iron, because of its material properties, also gives the added benefit of reduced noise stemming from internal damping. However, the lower fatigue strength of this material made it unsuitable for this application. In a study of ADI crankshafts, B. Kovacs found that the mean fatigue strength of ADI, when machined after Austempering, is more than twice that of pearlitic ductile iron[2] as shown in **Table 3**.

Table 3 - Mean Fatigue Strength of ADI Vs. Ductile Iron[2]

	Mean Fatigue Strength Nm (in-lb)
ADI	858.3 (7597)
Pearlitic Iron	410.5 (3634)

ADI - TVR was already using an ADI crankshaft in a different engine configuration, so it was a natural next step for this program. The ausferrite matrix of this material lends itself to mechanical dampening superior to that of ductile iron. Similar to its ductile iron counterpart, ADI can be cast to a near net shape, making manufacturing less difficult than that of steel. Even though some growth can occur during the heat treat process, the variation is predictable and can be accounted for in the design phase. The ADI crankshaft was rough machined prior to heat treat, and finish machine after heat treat to accommodate design tolerances.

Rough machining is accomplished rather easily when done prior to the Austempering process, which adds to the manufacturability of this material. **Figure 12** shows the relative machinability of ADI as compared to other ferrous materials. Note that the standard grades of ductile iron are easier to machine than ADI and most steels, thus it is advantageous to machine prior to Austempering. However, finish machining and fillet rolling done after heat-treating will increase the strength of the material. ADI is more expensive than ductile iron since a value added or heat treat process is included in the price. However, the cost of ADI is still lower than that of steel. Bahmani, et al, studied the manufacturability of ADI versus ductile iron castings and forged steels, and found a 30% cost savings using ADI over steel[1].

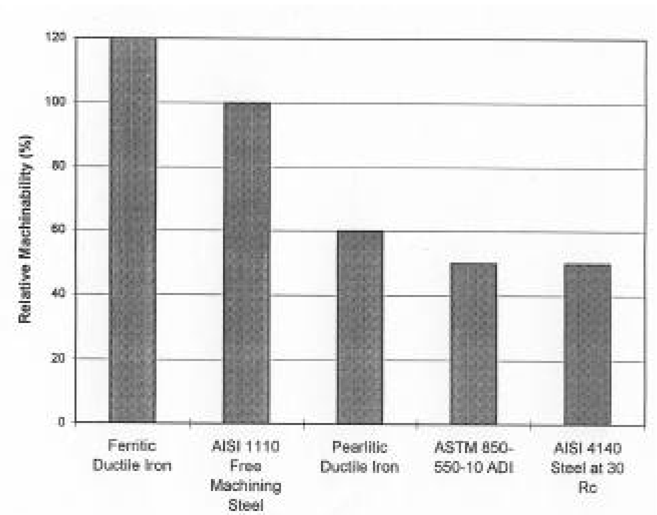


Figure 12 - Relative machinability of several ferrous materials.

ADI is 10% less dense than steel. This lower density provides a weight reduction opportunity compared to the steel crankshaft as shown in **Table 4**. A weight savings was a specific advantage for this high performance application. In addition, previous work by Kovacs on ADI crankshafts showed ADI to be stronger and more wear resistant[2].

Table 4 - Weight of production crankshafts

	Weight
Steel	34 kg (75 lbs)
Ductile Iron	29.9 kg (66 lbs)
ADI	29.5 kg (65 lbs)

As Chatterly and Murell discovered in their investigations of ADI crankshafts, the coefficient of thermal expansion in an ADI crankshaft needs to be considered[4]. The engine block, main bearing caps and bearing materials must be precisely chosen as indicated by the coefficient of thermal expansion data listed in **Table 5**. Panasiewicz, et al, also considered this in their 1991 study of ADI crankshafts. It was determined in this study that while an ADI crankshaft in an iron engine block may expand and seize the bearings, they are best suited in an aluminum engine block[3]. Bearing seizures encountered in earlier studies will not be repeated in an aluminum engine. This makes the use of ADI for the crankshaft material of the Speed Six engine a better choice for an aluminum engine block in the TVR vehicle.

Table 5 – Coefficients of Thermal Expansion[5]

	Coefficient of Thermal Expansion **mm/mm/Cx10^{-6} (in/in/Fx10^{-6})**
Steels / Irons	11 (6)
ADI (Grade 1)	14.6 (8.1)
Aluminum	22 (12)

CONCLUSION

TVR chose to use ADI as the material for their Tuscan Speed Six high performance sports car. Due to the density of the materials, ADI was lighter than steel. Being a cast product, ADI was more cost effective to produce than steel. This crankshaft was sufficiently strong compared to ductile iron to handle the loads of a high performance engine. The internal dampening effects of ADI also added the benefit of better NVH properties resulting in a quieter engine. By using ADI, TVR was able to save cost and weight while gaining better NVH properties, and still maintaining the strength and wear resistance needed in this application.

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ADDITIONAL SOURCES

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- www.ductile.org, The Ductile Iron Society