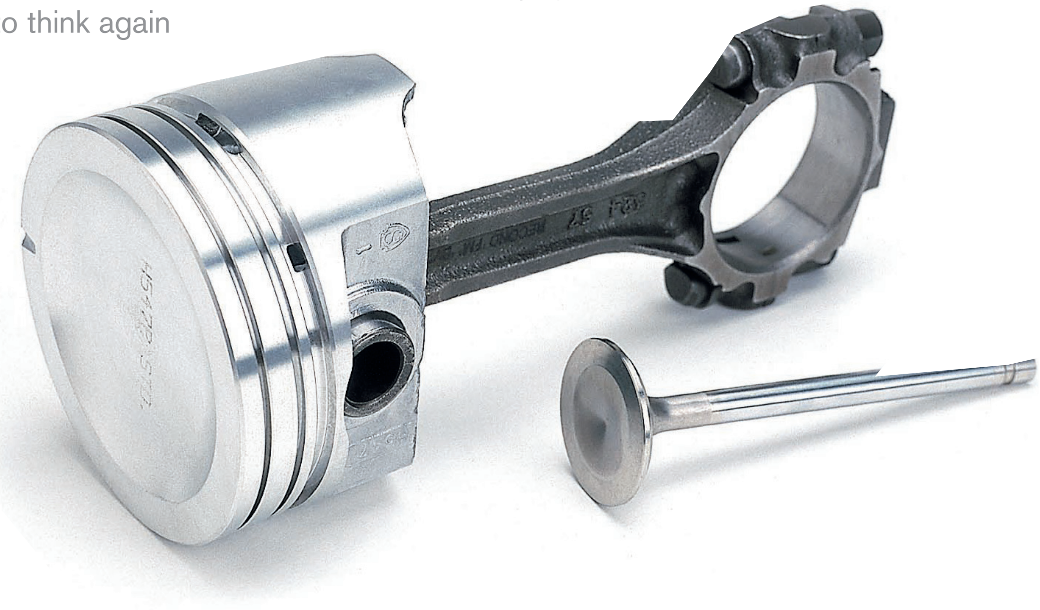
Supplied with kind permission of the author and *Racecar Engineering* magazine • www.racecar-engineering.com

# Icing the Cake

Most engineers think of heat treatment as a hot process. Deep Cryogenic Tempering will force them to think again

**By KEITH HOWARD**



Philip Harben, one of the earliest British television chefs, had a characteristically precise definition of cooking. He described it as 'the application of heat (or cold) to food to change its state'. We tend to think of cooking solely as heating; Harben was careful to include the fact that in some instances the transformation from raw ingredients to finished dish is achieved by cooling.

All of which has a curious resonance with recent advances in the heat treatment of metals. In many fields of motor sport savvy engineers have taken to passing engines, gears, brake rotors and other components to specialist companies who put them in freezers. Not the Westinghouse or Electrolux type, mind you, but freezers which use liquid nitrogen to cool their contents to around -185 degrees Celsius, less than 90 degrees above absolute zero. The process, called Deep Cryogenic Treatment or Tempering (DCT), which is often supplemented by gentle post-temper heating, acts to complete the material changes which conventional heat treatment (heating and quenching) starts but is unable to complete. The result is tougher, more durable components better equipped to withstand the rigors of motorsport.

The International Journal of Motorsport Technology
Racecar engineering
www.racecar-engineering.com

Practical DCT is only about a decade old. Although NASA began using it in the 1960s and a cryogenic facility was reportedly built at Los Alamos as early as 1952, early attempts at DCT produced inconsistent results. Because components were plunged directly into liquid nitrogen they were subject to extreme thermal shock which often did more harm than good. Less extreme cooling (Shallow Cryogenic Tempering), typically to -80 deg C, was tried but failed to produce optimum results. Only when a dry deep-cooling process was developed, and the cooling and warming rates put under precise computer control, was the potential of the procedure fully realised.

> *a cryogenic facility was reportedly built at Los Alamos as early as 1952*

Although it can be applied to a wide range of metals including aluminium, brass, copper, titanium and cast iron – it has even been used to improve the performance of musical instruments and baseball bats – DCT is best known for its application to various types of steel. In the tool making industry, for instance, it has already had a major impact through its considerable extension of tool life. A 200-400% increase in tool life after DCT is typical; with some tool steels the improvement exceeds 600%. Although cryogenic processing obviously adds to the price of a tool, that premium is dwarfed by material cost and by savings in maintenance and down-time.

In conventional heat treatment, steel is typically heated to around 900 deg C before being rapidly cooled (quenched) in water or oil. The heating process has the effect of transforming the steel into a soft solid phase called austenite. On rapid quenching most – typically 85% – of the austenite is converted into a much harder phase called martensite, which is responsible for the quenched steel's enhanced hardness. This comes at the cost of increased brittleness but subsequent tempering of the steel – raising its temperature to between 200 and 600 deg C and then cooling it in air – can offset this, restoring both ductility and toughness (the ability of the material to resist cracking).

Problems arise because of the so-called retained austenite – that fraction which isn't converted to martensite in the quenching process. This affects the physical and machining properties of the steel, and results in internal stresses which as well as weakening the metal can cause dimensional instabilities. With precision parts this may mean a regrinding process is necessary after heat treatment. Worse, as austenite can change spontaneously to martensite, especially if subject to large temperature changes, dimensional instability may recur when the part is in service.

The principal purpose of DCT is to convert the retained austenite to martensite and so obviate these deleterious effects. At the same time, the deep cooling of the steel precipitates carbon from the martensite matrix. During the mild heat tempering which usually follows DCT, this carbon is converted to carbides which enhance the strength and toughness of the material and imbue it with a hard, flat surface finish which generates less friction. The dense microstructure of the treated part also improves machinability. In contrast to surface hardening treatments like carburizing and nitriding, DCT is a once-only process that affects the entire structure of the component, so subsequent machining – for example, a crankshaft regrind – can be undertaken without any need for re-treatment.

The nature and extent of the metallurgical and physical changes has been quantified by research conducted at the Polytechnic Institute of Jassy in Romania. Shallow cryogenic treatment of M2 tool steel yielded the following results:

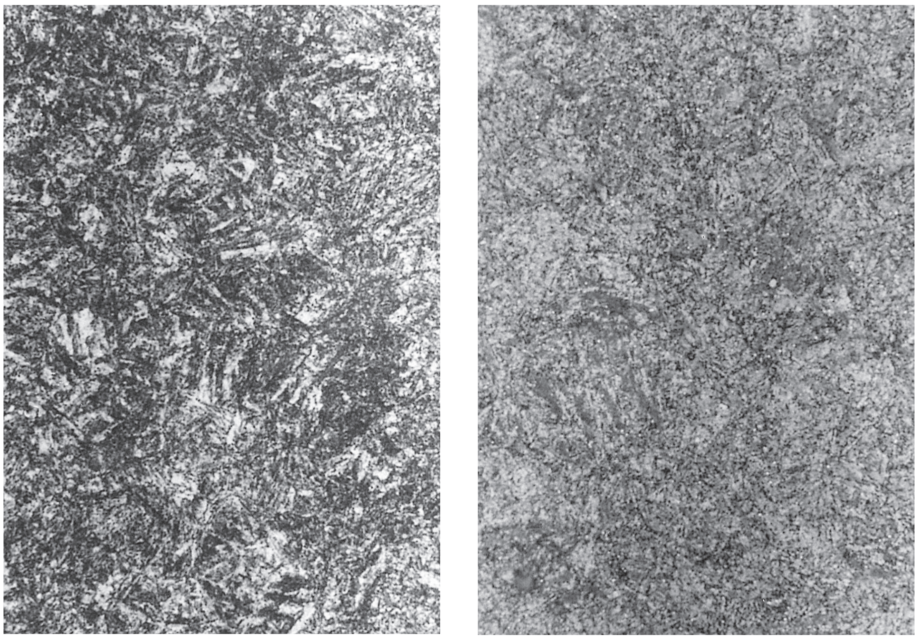
- austenite content decreased from 42.6 to 0.9%
- martensite content increased from 66 to 81.7%
- carbide content increased from 6.9 to 17.4%
- Rockwell hardness increased from 60.1 to 66.1
- **tool cutting life increased from 20 to 45 minutes**

Deep cryogenic treatment elicits even better results, typically doubling the material's wear resistance compared with the shallow alternative. Tests on five widely used tool steels conducted by Dr Randall Barron at Louisiana Tech University showed that shallow cryogenic cooling to -84 deg C elicited improvements in the range 1.2 to 2 times, whereas with deep cooling to -194 deg C the improvements were in the range 2 to 6.6 times.

DCT elicits the maximum benefit with steels that contain austenite and are responsive to heat treatment. If austenite is absent (as it is in 1020 low-carbon steel, for instance) or it is not amenable to heat treatment (as in the austenitic stainless steels) then DCT has negligible effect. In the case of metals other than steel, DCT's benefits arise from improvements to the crystal structure caused by the elimination of dislocations. Cryogenic treatment of copper welding rods, for instance, reduces their electrical resistance and thereby improves weld quality; DCT of cast aluminium notably enhances its machinability. Certain plastics can also benefit from DCT, and the technique is even applicable to amorphous materials such as glass.

DCT hardware is relatively simple. The parts to be treated are loaded at room temperature into an insulated chamber and then cooled by means of liquid nitrogen stored in an adjacent dewar flask. Different cryogenic equipment manufacturers use different methods of deploying the liquid nitrogen. It can be pumped through cool-

**The difference between treated (right) and untreated brake discs after the same amount of hard use**



**Untreated tool steel (below left) shows black feather-like martensite crystals. The white background is retained austenite which is transformed by DCT into stronger and more durable black martensite (right)**

ing coils within the chamber or introduced directly into it, immediate evaporation preventing the liquid nitrogen (which boils at -196 deg C) from coming into direct contact with the components being treated.

Different thermal cycles are used for different materials, the key requirement being to limit thermal stress. The rate of cooling is adjusted according to both the thermal conductivity and cross-section of the component, so that temperature differentials within it are kept small. A typical cooling rate is 0.5 deg C per minute, so this phase of the treatment cycle takes about six to seven hours. Once Ð-185 deg C has been reached it is held for an extended period – typically 24 to 36 hours – and the temperature then allowed to rise slowly back to ambient, again at about 0.5 deg C per minute. Mild heat tempering at 135 to 190 deg C is then applied if appropriate.

In the context of motorsport prices, the cost of DCT is relatively low. UK company Frozen Solid (www.frozensolid.co.uk), for example, charges about £475 for treating a complete four-cylinder engine, £285 for a gearbox (internals and case), £75 for a four-cylinder crankshaft and bearings, and £85 for a pair of brake discs.

> *Problems arise because of the so-called retained austenite*

Reported benefits are impressive, a good example being cast iron disc brake rotors. Diversified Cryogenics in the US conducted a back-to-back test of otherwise identical 13-inch brake discs, one of which had been cryogenically tempered and the other not. The untreated disc was run over 50 laps of Brainerd International Raceway using a racing friction material, at the completion of which the disc was sufficiently badly scored and cracked to be deemed unsafe – it was scrap. The treated disc was run for 56 laps with the same friction material and then an additional 35 laps with street pads (91 laps in total), at the completion of which it was judged good for a further 40 laps. In other words, the working life of the disc had been increased by a factor of 2.6. Because of the reduced warping and cracking of the disc, pad wear was also reduced by 40%.

Similar improvements have been reported from racing users, a doubling of disc and pad life being typical. In street use the improvements can be even greater. Cryocon Inc in the US (www.cryocon.org) has reported ambulance, taxi, police and other fleet operators enjoying increases in brake rotor service life of three to four times. Greg Bartlett of Frozen Solid sounds a warning, though, about the results being inconsistent from one disc manufacturer to another. Presumably because of differences in the constitution of the cast iron (certain trace elements such as titanium are known to have a significant influence on rotor performance), some manufacturers' discs show more pronounced improvements than others.

Other components which benefit from DCT include engine blocks, cylinder heads, camshafts, rocker arms, valves and valve springs, pistons and piston rings, conrods, crankshafts, bearing caps, clutch plates, gearboxes, final drives and drive shafts. Extended working life and enhanced reliability are not the only advantages: the reduced friction that results from the harder, smoother surface finish and improved dimensional stability produced by DCT can increase engine output and cut transmission losses, so that performance is improved too and cooling requirements relaxed.

Although DCT and its benefits are, as yet, not widely recognised in the motorsport world, its promise is such that it surely can't remain a secret weapon for long.

Components to be treated are placed in a container in which liquid Nitrogen is allowed to evaporate

*Photos courtesy of Cryocon*

CRYOCON

The International Journal of Motorsport Technology
Racecar engineering
www.racecar-engineering.com