GAS QUENCHING SINGLE COMPONENTS

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ABSTRACT

An extensive modelling study of cooling by means of nitrogen jets showed that an array of high velocity gas jets close to the surface of the part could produce cooling at about the same rate as oil. The optimum conditions required an approximately uniform nozzle field with the jets very close to the part and a gas velocity of 100 m/s. When these optimised conditions were applied to an idealised gear form, the model suggested that it could be fully hardened when a nitrogen-hydrogen mixture was used. Calculation suggested that in this type of nozzle field the part would float between the arrays, eliminating the need for fixturing.

Up to this point all the work had used CFD modelling. This type of modelling dramatically reduced the time taken to discover the optimum conditions but it had not been validated by experiment. Before it could be given a commercial application, the model had to be validated using a physical test rig. This showed that the model gave results very close to reality, which could predict the behaviour of production parts.

INTRODUCTION

An extensive modelling study was made of the cooling that could be achieved using an array of gas jets. It showed that under certain conditions they could produce cooling at about the same speed as oil (Stratton et al, 2000). The optimum conditions required an approximately uniform nozzle field with the jets about four to eight times their own diameter apart. The part to be quenched was at a distance of a quarter of the diameter of the jets and the jet velocity was 100 m/s. When the optimised conditions were applied to an idealised carburised gear, the model suggested that quenching using a 25% hydrogen/nitrogen mixture would fully harden the part (Stratton, 2001).

Calculations suggested that, under these conditions, most typical components would be levitated by the gas jets and would need no support or jigging during quenching (Stratton and Ho, 2000). The orientation of the component in this type of quenching is not important, as all sides see the same cooling, so the component can be oriented to give maximum lift. Levitation has the added advantage that circular components, such as gears, are free to rotate and improve even further the extremely uniform quenching achieved and so further minimise distortion.

Up to this point all the work had used CFD modelling. The model had dramatically reduced the time to discover the optimum conditions but it had not been validated by experiment. Before proceeding to commercial application it was necessary to validate the model using a physical test rig. This paper reports the results of those validation trials.

MODEL DESCRIPTION

When the rig had been constructed it was modelled with Fluent 6.0.12 using the same conditions that had been used previously (Stratton et al, 2000), except that some of the physical characteristics of the steel were replaced with more recent data and radiation losses were factored in.

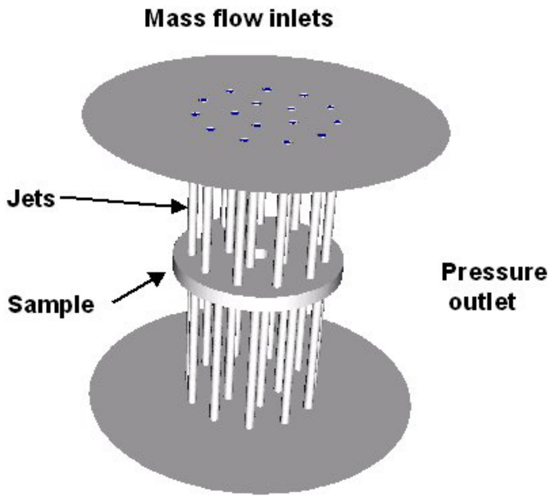

Figure 1: The model

The model domain was set at a 200 mm radius, almost twice the radius of the specimen and extended vertically to the gas distribution manifolds above and below the sample (200 mm total). The specimen and tube bank arrays to form the jets were thus centrally located within this cylindrical domain.

The model was meshed in two parts. The internals of the gas feed tubes and specimen itself was meshed using a regular hexahedral scheme (50,000 cells), whereas the gas space was meshed using a pyramidal scheme (800,000 cells). Attention was placed particularly on resolving the mesh near the tube tips and specimen surface. Owing to the need for different mesh densities in the specimen and in the gas flow space non-conformal interfaces were set up on the specimen boundaries. This allowed higher quality meshes with fewer cells to be generated for each region.

Initially the standard Fluent segregated solver was used together with first order discretisation for momentum,

energy and turbulence parameters with nitrogen simulated as an incompressible gas. The k-e turbulence model was also used with standard wall functions. An initial steady solution was achieved for a cold flow and then for a fixed hot sample temperature. During this period the mesh at the tips of the nozzles and on the surface of the sample were repeatedly adapted (refined) to ensure that the boundary layer assumptions of the model were within the valid range (Y^+ in the range 30-60).
The solver was then switched to the unsteady mode (1st order implicit) with a time step of 1 second. Although the maximum number of iterations per second was set to 100 to ensure a good degree of convergence each time step, the model would typically converge with considerably fewer iterations, especially towards the end of the simulation. Convergence criteria were set for normalized unscaled residuals of 10^{-3} for continuity, velocity and turbulence and 10^{-6} for energy and radiation with model mass and energy imbalances monitored periodically across boundaries. Calculations performed on a dual 1.7 GHz P4 processor Dell Precision workstation with 1 GB Ram took approximately 90 seconds per iteration. Time constraints and the close comparison with experimental results precluded extending this work to look at the effects of various modeling options e.g. higher order discretisation schemes, turbulence models and compressibility.

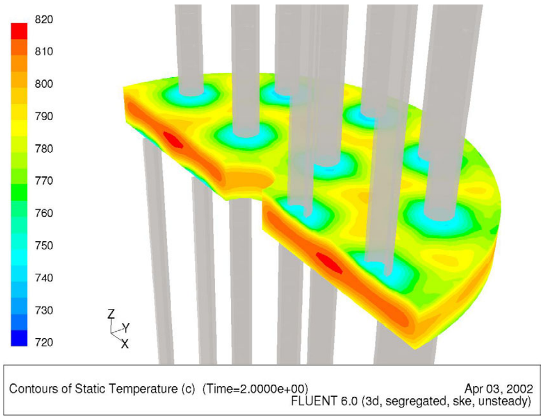

Figure 2: The temperature distribution after 2 seconds

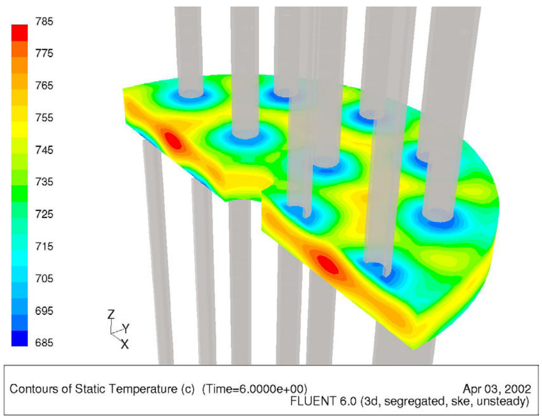

Figure 3: The temperature distribution after 6 seconds

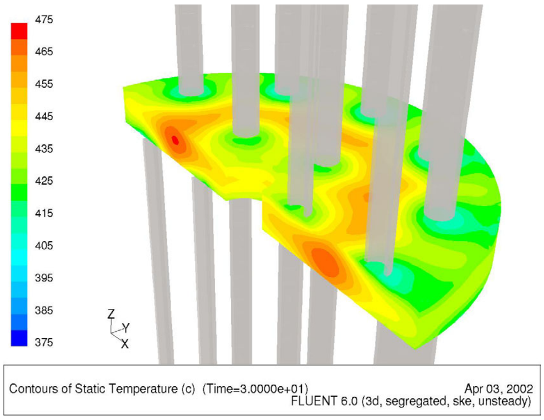

Figure 4: The temperature distribution after 30 seconds

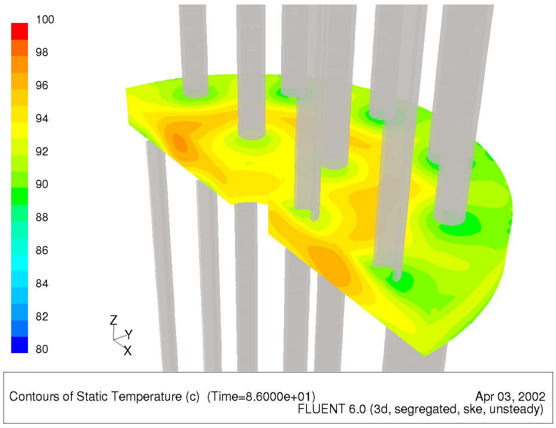

Figure 5: The temperature distribution after 86 seconds

Typical model outputs for 2, 6, 30 and 86 seconds quenching are shown in Figures 2 to 5 respectively. The model was also used to predict the cooling curve at the position of the thermocouple.
Figure 6 compares the predicted cooling curve for the core of the test piece in this experiment with that for the core of the web in the previous models that had the same cross-section.

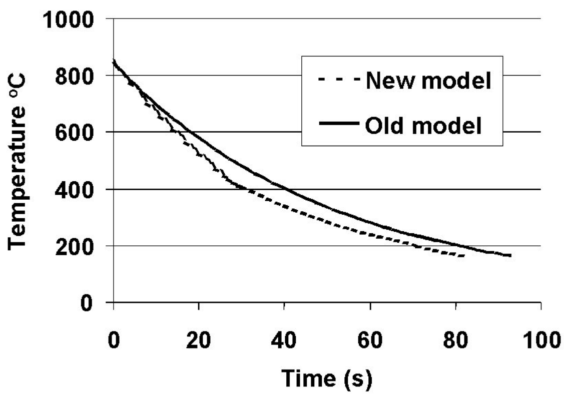

Figure 6: Old and new models compared

The two main differences of the later model are the use of temperature banded specific heat (Cp) data rather than an average, and the higher cooling rates at the higher temperatures due to radiation effects.

EXPERIMENTAL

Previous studies had shown that 25% hydrogen in nitrogen was needed to fully harden SAE 5120, although nitrogen alone gave a sufficiently high cooling rate to partially harden the core of such a steel. The quenching speed could therefore be inferred from the microstructure. In addition, it was considered too hazardous to use a flammable gas mixture in an open test rig under laboratory conditions. As an alternative a 25% helium in nitrogen mixture was used. Although too expensive for production use unless recycled, this mixture was expected to give quenching characteristics similar to the 25% hydrogen mixture and still be safe in a laboratory environment.

The test piece, selected to represent a simplified gear form, was a solid steel disk 110 mm diameter and 10 mm thick with a 14 mm hole in the middle and weighed approximately 0.75 kg. It was manufactured from AISI 5120 and subsequently carburised to a depth of approximately 1 mm. Some of the test pieces were drilled and thermocouples inserted to measure core temperature. Each thermocouple was placed at a point one-third the thickness of the sample and at half radius between the two circles of jets. This temperature measurement method had the disadvantage of restricting the free rotation of the test piece.

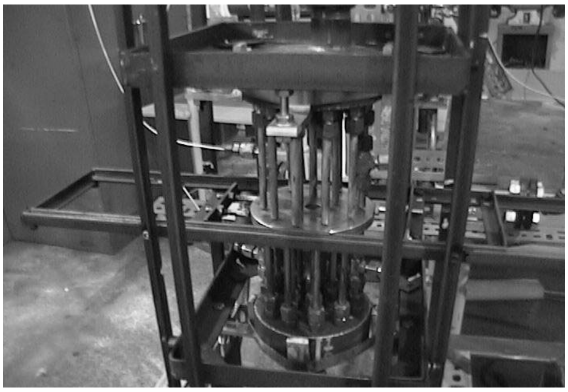

Figure 7: The test rig

The test rig (Figure7) consisted of two arrays of 16 x 4.57 mm internal diameter jets arranged as evenly as possible across the area of the test piece and meeting the optimised conditions. The individual jets were fed with nitrogen at a jet gas velocity of 100 m/s. The supply pressure needed to achieve the flow to the bottom-side jets had to be higher than that to the top-side jets because they also needed to levitate the test piece.

For the quenching trials the test pieces were heated in a Vulcan A550 box furnace and transported to the quenching rig down a specially designed slideway. It took approximately 30 seconds to get a test piece fitted with a trailing thermocouple in position in the rig, during which time it cooled. To compensate for this cooling these pieces were heated to a higher temperature than required.

LEVITATION TRIAL RESULTS

The initial levitation trials were carried out with a cold test piece. With the nitrogen velocity set at 100 m/s the test piece was successfully levitated and appeared to be exactly centred between the top and bottom jet arrays (Figure 8). It was noted that the test piece vibrated but the amplitude was not large and there was no contact with either jet array. The test piece rotated at approximately two revolutions per minute, probably because of slight irregularities in the flow field.

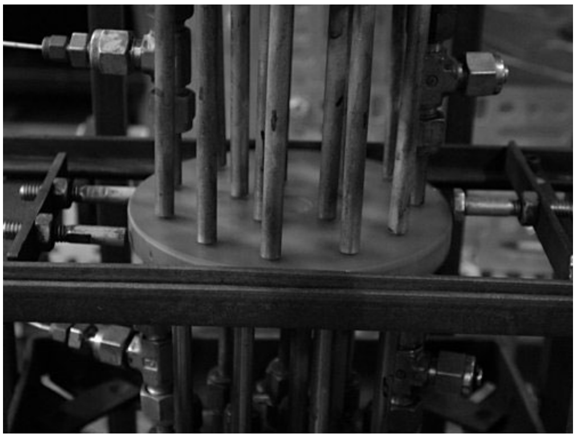

Figure 8: The levitated sample after approximately 2 seconds quenching

The pressure was recorded close to the tip of one instrumented jet in the top and bottom arrays, and the supply pressure necessary to achieve the required flow (Table 1) was also measured. Although great care was taken to ensure that top and bottom arrays were physically identical, tiny differences in the packing of the plenum chambers could have resulted in the slightly different pressure drop for each array.

	Top array	**Bottom array**
Pressure at flow meter (barg)	5.1	5.2
Pressure at jet tip (barg)	0.16	0.34

Table 1: Pressures at 100 m/s Gas Velocity

The supply pressures required were well within the range typically available from a standard liquid nitrogen supply system with ambient temperature vaporisation.

The difference between the top and bottom jet tip pressure (0.18 barg) equates to a lifting pressure of 0.46 kg when integrated across the cross sectional area of the apertures in the jet array. However the pressure cannot fall until the flow has passed beyond the annulus between the test piece and the jet because the annulus has the same area as the aperture. Therefore the whole area of the jet including its wall must be considered when calculating lifting power. This calculation gives a lifting power of 0.83 kg, very close to the actual weight of the test piece and within experimental error.

INSTRUMENTED QUENCH TESTS

Several quenching runs were carried out using both instrumented and non-instrumented test pieces. The cooling and cooling rate curves are shown in Figure 9.

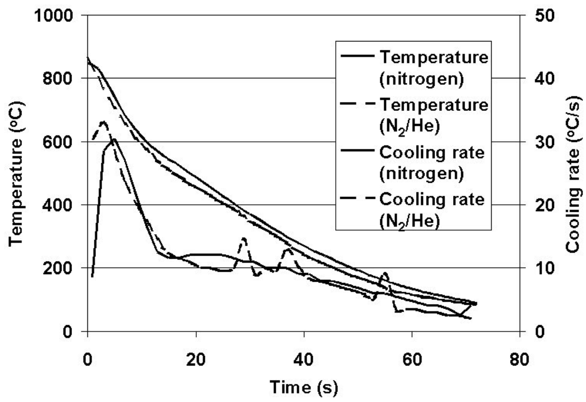

Figure 9: The cooling curve and cooling rate for different gas mixtures v quenching time

The data presented in Figure 9 clearly show that the addition of helium has only a small effect on quenching, increasing cooling. If the cooling curves in Figure 9 are compared to those for a typical medium quench oil (Figure 10) it can be seen that the time taken to reach 600°C is almost identical for all three media. Below this temperature the oil is faster down to 200°C, but this is unlikely to affect microstructure unless the bainite nose for the material being quenched occurs at unusually short times in the TTT diagram. If a slower cooling rate is required at any time during the quench, it can be achieved by simply reducing the quench gas velocity or stopping the flow altogether and allowing the component to cool in still gas.
This data suggests that in practice there is little difference in quenching rate using gas mixtures when applying this technology. However, a small hydrogen addition would have a significant advantage in greater cleanliness of the processed components, as it would keep them oxide free.

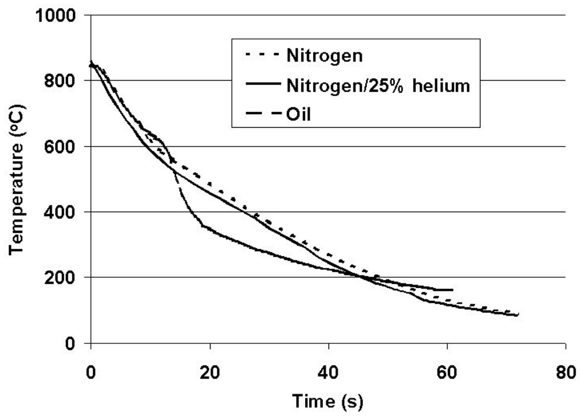

Figure 10: The quenching rate of nitrogen and a nitrogen/helium mixture compared to medium quench oil

Comparing the cooling curves predicted by the model with the actual results (Figure 11) shows that the model still under predicts the cooling rate despite the changes made to the model to allow for radiation losses.

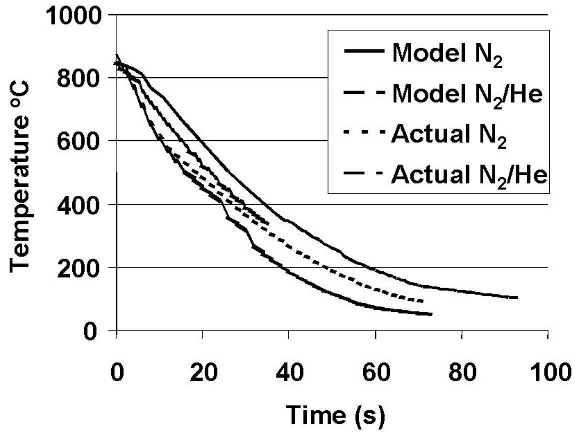

Figure 11: Predicted v actual cooling rates for nitrogen and nitrogen/25% helium

It was suggested that the equilibrium Cp values used for the model were inappropriate for continuous cooling conditions (Segerberg, 2002). Cp values appropriate to the phases present at the time derived from the continuous cooling curve were substituted with the results shown in Figure 12. The match with the experimental data was now almost exact.

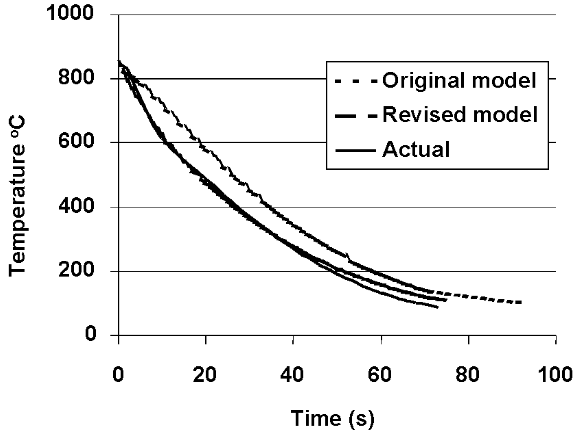

Figure 12: Comparison of the original and revised model quenching curves with the experimental data

TESTING CARBURISED SAMPLES

Some samples were pre-carburised to a nominal 1 mm case depth and cooled out. They were then reheated and quenched in the two gas mixtures and in a medium quench oil as a reference. The mean hardness profiles for all three methods of quenching are compared in Figure 12. The effect of the cool and reheat is obvious for all three quenching methods. The fall in hardness towards the surface is due to carbon loss during cooling and reheating, rather than to the presence of retained austenite.

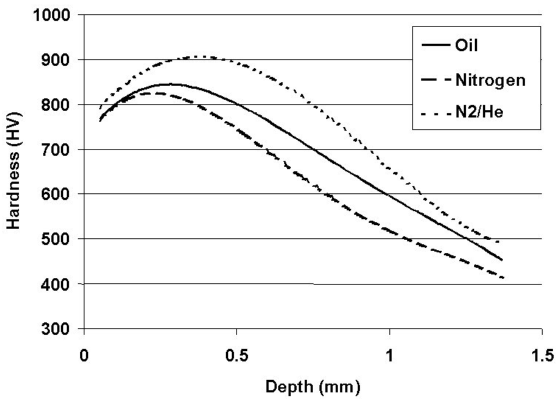

Figure 12: The mean hardness profile of samples quenched in nitrogen and a nitrogen/helium mixture compared to medium quench oil

Figure 12 shows clearly that the small differences in cooling rate between nitrogen and nitrogen/25% helium found in the instrumented trials had a significant effect on hardening. These differences in the hardening of the case were not reflected in the mean core hardness achieved.

Quench medium	Mean core hardness (HV)
Medium oil	353
Nitrogen	343
Nitrogen/25% helium	350

Table 2: Core hardness after quenching

The core hardness (average of 20 tests) produced by each technique is very similar, as are the core microstructures shown in Figure 13. However, there is evidence of small amounts of ferrite in the oil and nitrogen quenched samples which is absent in the nitrogen/25%helium quenched sample, indicating a slightly faster quench in the last case.

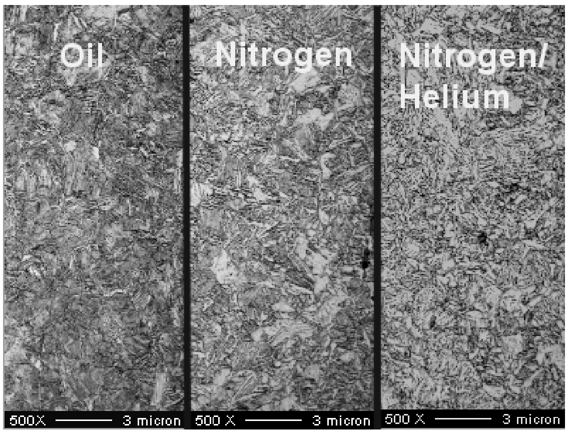

Figure 13: The microstructure of the core of samples quenched in nitrogen and a nitrogen/helium mixture, compared to medium quench oil

The appearance on the macroscopic scale of the three case structures is very similar as shown in Figure 14. This suggests that the differences in depth of hardening were caused by the difference in quenching rate and not by variations in carbon penetration during carburising.

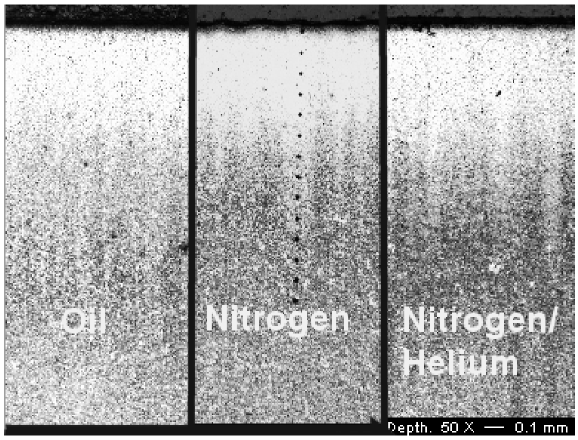

Figure 14: The microstructure of the case of samples quenched in nitrogen and a nitrogen/helium mixture, compared to medium quench oil

CONCLUSION

Using a suitable array of gas jets it is possible to levitate a component during quenching, eliminating the need for conventional jigging. The quenching rate that can be achieved with nitrogen alone as the quenching gas is very similar to that produced by a medium quench oil. The cooling rate when using a higher thermal conductivity mixture such as nitrogen/25% helium is slightly higher. The Fluent model accurately predicts the cooling rate that can be achieved.

Carburised gear blanks 10 mm thick manufactured from AISI 5120 are almost fully hardened using nitrogen alone as the quenchant. If nitrogen/25% helium is used as the quenchant, the properties exceed those obtained by oil quenching.

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