WEAR PERFORMANCE OF COMPOSITIONS MADE BY
LOW ALLOY IRON/HIGH ALLOY POWDER MIXTURES

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ABSTRACT

A practical solution to wear and rolling contact fatigue problems may be
found in the area of composite materials created by the blending of powders
to produce materials which obtain advantageous properties by combining the
properties of the individual components in the powder blend. This paper
reports laboratory test methods and procedures developed to assess the
properties of such blends in rolling contact fatigue and wear.

Blends of a prealloyed 4600 type powder, a modified tool steel powder,
carbon and copper have been prepared and sintered using a sinter furnace
hardening process. The sintered components have been tempered after
sintering and tested in laboratory rolling contact fatigue and wear
simulations.

The results of these tests indicate that such materials have rolling contact
fatigue properties that are as good as conventional sintered material and
show improved wear resistance. A preliminary model to explain these results
is proposed. The conclusion from this work is that the approach of composite
powder blends provides sufficient benefit to continue development programmes
in this area.

INTRODUCTION

Many components in everyday use are exposed to combinations of cyclic
stress and sliding wear. Examples of this can be found in many parts which
exist in pairs and are in relative motion such as, cams and cam followers,
gears and roller bearings. Components subjected to such operating conditions
often fail by mechanisms involving wear (adhesive or abrasive) and rolling
contact fatigue. The extent to which any given mechanism will contribute to
failure depends on the details of the system. Failures due to these
mechanisms are typified by loss of surface material either by the generation
of cracks in the material or by adhesion and pull out of one or other of the two surfaces. To further emphasise the relation between wear properties and rolling contact fatigue, the latter is commonly thought of as a wear mode in its own right by tribologists.

As with many materials selection problems an ideal material to combat both forms of wear at the same time is difficult or impossible to find. On a basic level we might propose a very hard material to prevent surface erosion by adhesive or abrasive wear but would then find that the material was prone to rapid crack growth and hence failure by rolling contact fatigue type mechanisms.

One solution to such a problem is the use of composites of which a prime, although not obvious, example is the case hardened gear where a hard surface is generated supported by a less hard but tougher material. Powder metallurgy can also be used to produce composites by blending powders of different compositions, and hence properties, prior to pressing and sintering. There are several conditions that must be satisfied for this to be successful:

a) A good bond must be developed between the various powder species.

b) The various powder species must retain or generate their individual compositions during processing.

c) Processing conditions must be developed which create appropriate properties in the various powder species.

d) The compressibility of the powder mix must be sufficient to allow the pressing of reasonably high density green compacts.

For many years now tool steel powders have been available and have been used in the large scale production of valve seat inserts. However, the cost of tool steel powders is relatively high and, while having good wear resistance, they do not necessarily have good rolling contact fatigue properties. Additional problems arise in that the bond between standard grades of tool steel powders and lower alloy powders is not necessarily strong and the compressibility of a powder mix containing tool steel powder can be reduced significantly.

This paper reports work which has been carried out at Powdrex and Zenith Sintered Products on the development of sintered materials created by blending various amounts of a prealloyed 4600 type and a tool steel powder modified to produce high compressibility and to promote good bonding with the 4600 during sintering. The paper further discusses the testing procedures used to determine the materials suitability for wear and rolling contact fatigue applications. While the complexity of in service wear behaviour requires that final testing should always be in service this is simply not possible in producing basic data for a new family of materials. As a result Zenith and Powdrex have developed test rigs and procedures which enable us to screen new materials in house before embarking on expensive and time consuming field trials. The paper concludes by providing the results of such testing on the above materials and attempts to propose mechanisms which might explain the results.
EXPERIMENTAL

A range of blends were prepared using various ratios of modified tool steel and 4600 powder mixes containing from 0 to 20 weight % of tool steel. The blends contained sufficient carbon to raise the total carbon content to 0.9wt% and 2wt% copper was added to provide materials suitable for air hardening. Compressibility curves were generated and the test samples were pressed to 7.17 g/cc. Parts for wear and rolling contact fatigue testing were produced by pre sintering and machining prior to final sintering and tempering.

After final sintering at 2070°F, using a sinter furnace hardening treatment involving hardening as part of the sintering stage, the materials were tempered for two hours at 350°F. Details of sinter furnace hardened material and the effect of sinter temperature and density on rolling contact fatigue properties are reported elsewhere at this conference [1].

WEAR TESTING

Wear testing has been carried out using a modified and reinstrumented Falex block on ring wear test machine, a schematic of this is shown in fig. 1.

![Schematic Diagram](image)

Figure 1. Schematic diagram showing the Falex wear rig arrangement.

The test arrangement consists of a sample in the form of a stationary block (0.62 inch long, 0.4 inch high and 0.177 inch wide) and a standard AISI 4620 Falex wear ring (1.3775 inch diameter and 0.3437 inch width) , 58-63 HRC, rotated beneath it. Details of the standard test arrangement can be found in ref. 2. The frictional force is measured by a load cell which measures the force transmitted from the rotating ring to the specimen through friction and is measured tangentially to the ring. A schematic wear test chart is
shown in fig. 2. In general the frictional force fluctuates about the average value shown in the schematic.

In stage one a fixed load of 3.75 Kg is applied to the block while the ring is rotated at 250 rpm for 1 hour. The ring and the block are weighed before and after this period to determine the degree of wear. The ring and block are returned to the wear rig and run for a further 15 minutes, the load is then increased by 1.5 Kg and by a further 1.5 Kg every 5 minutes. In the series of tests reported here the total test time was 155 minutes resulting a final load of 27.75 Kg. Throughout the test the frictional force was monitored.

\[ \text{Figure 2. Schematic diagram showing frictional force output during the wear testing procedure} \]

In principle this type of test should be able to provide fundamental information about the reaction of the two mating surfaces under a given test condition. However, there are a number of complications which apply to any wear testing. The most important of these is the actual interface condition at the time of measurement.

Due to the nature of wear testing a significant amount of heat is generated. This has the result that the actual interface conditions may not be those that are expected, for example, oxide layers are formed which modify the interface interactions. Thus, in stepped load testing, the increasing load will vary the friction conditions continuously throughout the test. There is extensive literature available concerning the role of oxides and chemical reaction effects at the interface [3,4] but these aspects will not be considered further here.

The use of composites complicates matters still further as various aspects of the material will behave in different ways at different times. We are, therefore, in a position where interpretation of results, at least in the early stages of development, requires considerable inspirational guesswork.
The test procedure used at Zenith has been designed to provide sufficient information to allow reasonable extrapolations and consists of a dynamic equilibrium condition in a low load mode followed by short term stepped testing where interpretation is of the essence.

What must be remembered is the dual nature of the experimentation. While comparative results can be generated by testing different materials under the same conditions we must also try to understand the features that generate the results so that we can extrapolate them to real situations.

ROLLING CONTACT FATIGUE TESTING

As far as we can ascertain there is very little work that has been carried out on the rolling contact fatigue testing of PM materials under truly controlled situations. In an attempt to obtain information Powdrex have developed the rolling contact fatigue rig described below, shown schematically in fig. 3 and reported in more detail in ref. 5.

![Diagram of rolling contact fatigue rig](image)

Figure 3. Schematic diagram showing the rolling contact fatigue rig arrangement.

To provide an example of the complexity of the situation the geometry of the test system critically affects the stress being generated. In the current test set up spherically ground rollers and a cylindrical specimen are used. The maximum surface pressure generated by this system is given by [6]:

$$\text{Max Surface Pressure} = \frac{3P}{2\pi mnz^2}$$

Where

$$z^3 = \frac{3P(1-v^2)(1/E_1+1/E_2)}{2(2/R_1+1/R_2)}$$
Subscript 1 refers to the rollers and subscript 2 to the sample

\[ P = \text{Force applied to the rollers} \]
\[ \mu \text{ and } \eta \text{ are constants related to the geometry} \]
\[ \nu = \text{Poisson's ratio, (assumed the same for rollers and sample)} \]
\[ E = \text{Young's modulus} \]
\[ R = \text{Radius of sample or sphere.} \]

The maximum sub-surface shear stress which exists at a small depth beneath the surface of the sample is given by approximately 0.31 times the maximum surface pressure.

Looking at the above equation a further point of importance can be seen and that is the effect of the sample Young's modulus. This critically affects the stresses generated in the sample as it determines the degree of local deformation. In general, steels can be considered to have a Young's modulus of 207 GPa. However, when we start dealing with porous materials, this value can change significantly as reported by Danninger [7]. In this reference the reduction in Young's modulus is reported to be very rapid with increasing porosity. Working values for the Young's modulus of a PM part containing 10% porosity would be about 71% of the full density value and this would further reduce to 43% of the full value at 20% porosity.

A reduction in the Young's modulus results in an increase in the contact area and so the stress levels which a PM part experiences are less than those experienced by a solid part under the same loading conditions. Unfortunately, the resistance to fatigue failure also falls with increasing porosity. The result of this is that there must be a tradeoff in design terms between the reduced loads generated in the wear parts and the rolling contact fatigue life that can be obtained from a PM part. As part of a major project not reported here Powdrex are carrying out extensive work on the affect of PM component parameters on the rolling contact fatigue life of PM parts.

The mechanics of the rolling contact fatigue test are briefly described below. A cylindrical specimen is loaded between two spherically ground hard metal rollers. The load is applied using a cantilever arm which transmits the load to the top roller. The specimen is held in a floating carriage so that the sample is loaded at both contact points of the rollers. The whole system is lubricated with a constant flow of oil at a fixed temperature to simulate working temperatures (typically 212°F) and the upper and lower rollers are driven at 1400rpm. This drives the specimen and so each point of the sample surface is loaded twice per revolution. Stroboscopic measurements have shown that there is insignificant slippage between the rollers and the specimen and so the surface of the specimen is subjected to pure rolling contact stresses.

Failure of the specimen is caused by the loss of material from the surface of the sample and this causes an increase in the vibration level of the upper arm at a frequency specific to the rotation speed of the specimen. In the latest modification to the apparatus this vibration is detected by a piezo electric accelerometer. The output from this is collected by a computer, passed through a fast fourier transform package and an amplitude/frequency plot generated. After the selection of the specific frequency to be monitored, the computer produces an ongoing trend plot of
the amplitude of this frequency. Failure of the specimen is determined by a
marked increase in the amplitude of the specific frequency and, when this
exceeds a preset threshold, the machine is automatically turned off.

Visual observations of specimens which have been tested in this way show
that in most cases the instrumentation is capable of detecting failure
within a few seconds and the sample can then be removed for further
examination.

The results obtained from this test are time to failure and the load used.
The actual stresses to which the sample was subjected are calculated using
the methods described in Timoshenko & Goodier [6]. In order to obtain
results in a reasonable time fairly high loads are used to give relatively
short lives and the results are then extrapolated to give the stress
supported to a given number of cycles. In order to do this various
functional approximations to the S/N curves must be used. The figures quoted
here assume that the life reduces by a factor of ten when the load is
doubled. The shear stresses supported to a given number of cycles can then
be calculated. These approximations can only be considered to be rules of
thumb and will remain so until true long term low load testing can be
carried out to determine the relationship experimentally. A more detailed
discussion of the considerations required in this type of accelerated
testing can be found in ref. 8.

The results quoted in this paper are in the form of maximum shear stress
levels supported to 200 million cycles but have all been generated using the
same test load and are thus directly comparable. The effect of the
approximations is to make the absolute values open to question.

RESULTS

Compressibility

Fig. 4 shows the green densities achieved at various pressing pressures for
the full range of 4600 and tool steel blends investigated. While there is a
reduction in the compressibility of the powder mixes the effect is not
large.

Transverse rupture strength

Fig. 5 shows the transverse rupture strength for sintered blends of 4600
blends containing 0, 15 and 20% tool steel having densities ranging from 6.8
to 7.2 g/cc. It is clear from this graph that the density of the sample is a
far more important factor than the amount of tool steel powder in the
sample.

Rolling contact fatigue

Fig. 6 shows the effect of tool steel content on the rolling contact fatigue
load supported to 200 million cycles. This has been calculated by carrying
out high load testing and extrapolating the results to lower loads. The
results clearly show a slight increase in the shear stress supported with
increasing tool steel content. It was originally thought that the addition
of tool steel powder would slightly reduce the rolling contact fatigue
properties. However, the slight increase in rolling contact fatigue
properties can be readily explained in terms of solid solution strengthening of the less highly alloyed material.

Figure 4. Graph showing the effect of tool steel concentration on compressibility at various pressing pressures.

Figure 5. Graph showing the transverse rupture strength of sintered parts containing various amounts of tool steel at various densities.
Figure 6. Graph showing the maximum sub-surface shear stress supported to 200,000,000 cycles by sintered parts with various amounts of tool steel.

It is clear from the TRS results and examination of the microstructures shown in fig. 7 that good bonding is obtained between the 4600 and the tool steel and this means that a certain amount of diffusion will have occurred across the sinter necks. This will result in strengthening of the 4600 in exactly those regions where strengthening will be most useful. Furthermore, it is to be expected that a considerable portion of the fatigue behaviour will be determined by the porosity and its structure and this will not be greatly affected by the presence of two powder components.

Figure 7. Micrographs showing a sintered blend of 4600 and modified tool steel. Photomicrograph (a) shows the microstructure at the boundaries of the two phases which show no signs of the prior particle boundaries. Photomicrograph (b) shows the even dispersion of the tool steel in the 4600 matrix.
Wear results

The wear results obtained are not as straightforward as the rolling contact fatigue results and a number of test parameters have been recorded. These are shown in Table 1 and graphically in figs. 8 and 9. In all cases the material varied was the block.

A number of things are immediately clear.

i) The friction measurement made during the first hour of running under low load shows a marked downward trend as the amount of tool steel is increased. This indicates that the tool steel component is affecting the interactions at the material interface.

ii) The overall wear as measured by weight loss show a marked reducing trend under low load testing and a slight reducing trend after stepped higher load testing. This indicates that the mating pair has an improved wear resistance overall compared with the plain 4600 material without the addition of any tool steel powder.

Looking more closely at the relative wear of the two components of the mating pair we find that the wear behaviour is different in the two regimes of wear testing. This can be seen by plotting the wear of the pin and the wear of the ring separately. When this is done we find that at low loads, Stage one, the wear on the block is very low and remains almost constant while the wear of the ring decreases rapidly with increasing tool steel content.

<table>
<thead>
<tr>
<th>Tool Steel, Wt %</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRICTIONAL FORCE, Kg.</td>
<td>2</td>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>RING WEIGHT LOSS</td>
<td>2.2</td>
<td>1.6</td>
<td>1.6</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>BLOCK WEIGHT LOSS</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>TOTAL WEIGHT LOSS</td>
<td>2.7</td>
<td>2.1</td>
<td>1.9</td>
<td>1.2</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**STAGE 2**

<table>
<thead>
<tr>
<th>Tool Steel, Wt %</th>
<th>0</th>
<th>3</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>RING WEIGHT LOSS</td>
<td>24.5</td>
<td>26.7</td>
<td>22.4</td>
<td>26.9</td>
<td>20.1</td>
<td>17.9</td>
<td>26.9</td>
</tr>
<tr>
<td>BLOCK WEIGHT LOSS</td>
<td>10.0</td>
<td>14.0</td>
<td>12.2</td>
<td>6.1</td>
<td>7.0</td>
<td>6.6</td>
<td>5.6</td>
</tr>
<tr>
<td>TOTAL WEIGHT LOSS</td>
<td>34.5</td>
<td>40.7</td>
<td>34.6</td>
<td>33.0</td>
<td>27.2</td>
<td>24.5</td>
<td>32.4</td>
</tr>
</tbody>
</table>

**Table 1**

**WEAR TESTING RESULTS**

NOTE: Weight loss is quoted in micrograms.

**Block appearance**

- Smearred
- Smoother
- Smoothest

**Ring appearance**

- Even Wear
- Slight Scoring
- Patchy Dark Areas
Figure 8. Graph showing weight loss of the block, the ring, and the wear couple during Stage 1 wear testing.

In the case of the stepped load testing, Stage two, a different relationship is found. Obviously the overall wear of both components is greater after the stepped load testing but in this case we find that the wear of the ring remains approximately constant while the wear of the block reaches a low level from 9% tool steel content upward. The combination of wear for both components shows a slight downward trend although anomalies appear at the two extremes of tool steel concentration.

At this stage of our investigations we have not yet studied the wear surfaces in detail in order to ascertain what sort of changes are occurring. However, a possible hypothesis for this behaviour is laid out below.

**DISCUSSION OF RESULTS**

Rolling contact fatigue.

The results obtained to date indicate that there is a slight increase in the resistance to RCF failure with increasing tool steel powder content. This, along with the TRS results and the microstructural appearance indicates that good bonding is obtained along with some solid solution strengthening at the sinter necks in the composite powder mix. In any event it appears that a composite of this type can be used as a direct replacement for PM components without a reduction in the rolling contact fatigue life. Further work is required to determine whether or not further improvements can be made by modifying the sintered interfaces and the chemical compositions that are present at the sintered boundaries.
Figure 9. Graph showing weight loss of the block, the ring, and the wear couple during Stage 2 wear testing

Wear results

Again further investigations are required to elucidate the mechanisms and reactions that are occurring during the test. As a first stage of this investigation we are proposing a model which seeks to explain the observed behaviour.

A model must take into account that at the interface between the composite block and the ring there are a minimum of two possible interactions, i.e. that between the ring and the tool steel and that between the ring and the 4600. In the series of experiments reported here we can isolate the reaction between the 4600 and the ring by reference to the tests carried out without the addition of any tool steel.

Looking first at the effect of tool steel additions on the initial friction values. This shows that the friction value decreases with increasing amounts of tool steel. This can be interpreted as showing that the interaction, in terms of frictional forces, between the tool steel particles and the ring material is less than that between the matrix and the ring material. This will have the effect of reducing the heat generated at the interface during the test.

In the low load test we can hypothesise that hard wearing tool steel particles stand slightly proud of the block surface and so the reduction in frictional force due to the tool steel is greater than might be expected.
based solely on the tool steel content. The degree of the reduction will depend on the amount of the matrix which is actually in contact with the wheel. Further extrapolation of the trend would suggest that the frictional force would eventually reach zero. Clearly this is a practical nonsense and we would expect the frictional force to level off once the interparticle spacing of the tool steel reaches a critical value.

In this low load and dynamic equilibrium regime it can be seen that the wear of the block remains roughly constant while the wheel wear decreases. We must therefore propose that under this condition the mating pair of the ring and the tool steel particles results in lower ring wear than that of the ring mating with the matrix material. This may be due to the reduction in heat generated at the contact points. As the amount of tool steel powder increases less and less of the matrix material can come into contact with the ring due to the supportive nature of the tool steel particles and so the wear of the ring material is gradually reduced.

We must also propose that the rate of wear of the block is determined by the ease with which the supporting particles of the tool steel can be worn away allowing new areas of the matrix to come into contact with the ring. Over the range of tool steel concentrations which we are considering we can propose that the rate of wear of each individual particle is constant and is not affected by the rate of wear of its neighbours and so the rate at which the block is worn away will be independent of the tool steel concentration.

The change in the wear behaviour of the block and the ring under higher step load testing implies that the wear mechanisms have altered at some point during the test. Interpretation of these results is complicated by the fact that we are only looking at the average amount of wear that has occurred over the whole test during which various loads have been employed.

In this regime we propose that the increased load causes the tool steel particles to start to dig into the surface of the ring material. In this case ring wear is caused by two mechanisms:

i) Removal of material due to the scouring effect of the tool steel particles.

ii) Adhesive wear between the ring material and the matrix.

Once the tool steel particles have penetrated the surface sufficiently the 4600 matrix will come into contact with the ring. At the levels of tool steel powder investigated here, once contact with the matrix has been achieved removal of material from the ring will be dominated by the ring/matrix wear and so the rate of wear will be only slightly affected by the amount of tool steel present. In the case where no tool steel is present there does appear to be an anomaly in the amount of material removed from the ring. This may be the result of natural variation in the test method or it may be related to the scouring effect of any level of tool steel content which could aid in the removal of ring material by aiding the detachment of smears from the ring surface.

In order to explain a reduction in the rate of wear of the block we can propose that the presence of the tool steel particles locally strengthens areas of the matrix and makes them more resistant to removal of material by
the ring. Thus as the amount of tool steel is increased the rate of wear of the block will be reduced.

One further piece of information needs to be taken into account and that is the apparent condition of the block and the ring after the tests. While this is to a large extent subjective it has been found that with 0% tool steel addition the block shows a degree of material smearing while the ring shows an even wear pattern. This can be interpreted in terms of the above model to indicate that when the matrix and the ring are in contact total wear is dominated by smearing and removal of the matrix material. As the amount of tool steel increases the wear scar on the block becomes smoother suggesting that the material is becoming more resistant to material removal. On the other hand the ring starts to show signs of scoring which is probably due to the scouring effect of the tool steel particles.

Much of the above must be considered to be hypothetical but as can be seen the possible variations and complications in wear testing make an exact analysis almost impossible. It is also clear that there is a vast field for further investigation but of particular interest is the topology of the wear scars produced. Such information can readily be obtained using SEM’s. What is, however, clear is that for the mating pair tested in this work the overall wear rate is reduced when tool steel is added to the matrix material and the use of a composite powder metallurgy material does significantly affect the wear behaviour of a wear couple.

CONCLUSIONS

Mixtures of tool steel powder modified to allow good bonding with 4600 material can readily be sintered using the SFH process as practised at Zenith. Tempering of the material can be carried out as sintered without the need for additional solution treating and can produce materials with physical properties which are not reduced with respect to the parent matrix material.

These materials have particular benefits in the realm of wear and rolling contact fatigue applications. Rolling contact fatigue is slightly improved, probably due to solid solution strengthening and the wear resistance of the material when coupled with 4620 material is increased due to the reduced interaction between a tool steel and 4620.

Considerable scope remains for developments in the area of composite powder materials and the results from this preliminary work provide sufficient encouragement for the continuation of our current programmes.
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