

## THE BALL CRATER TEST FOR DETERMINING THE ABRASIVE WEAR RESISTANCE OF MATERIALS - SOME UNEXPECTED RESULTS

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### Introduction

The ball crater wear test has attracted the attention of people involved in surface engineering and beyond because of its simplicity, its possibility of varying the abrasive contact parameters and, last but not least, because it allows the measurement of local properties on simple test geometries as well as on real coated components.

In this paper, some results are presented of preliminary, simple and straightforward experiments as a first evaluation of the performance of the technique. It was found that quite often, unexpected results are obtained. Studies are underway in the attempt to explain the observed phenomena.

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### Experimental details

The TE66 micro-scale abrasion tester manufactured by Plint was used. As opposed to other ball crater rigs available on the market, this instrument allows the independent selection of the contact load, ball material and rotational speed, and the number of revolutions (or sliding distance). The ball is rigidly held into the rotating shaft and the test surface is mounted on a counterbalanced beam that hangs vertically from a pivot (fig. 1). A separate peristaltic pump was used, instead of the one coupled to the drive shaft, to enable the independent control of the abrasive slurry supply.

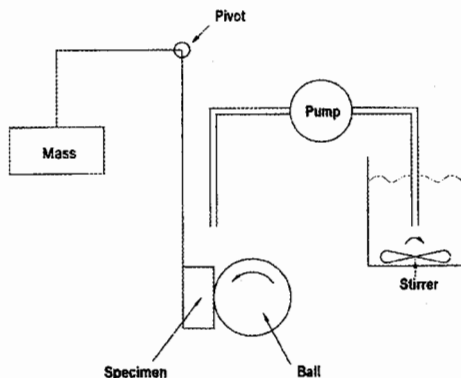


Figure 1: Schematic of the ball crater test rig.

For homogeneous bulk materials, the wear factor (ratio of wear volume to the contact force and sliding distance, unit  $\text{m}^3/\text{N}\cdot\text{m}$  or  $\text{m}^2/\text{N}$ ) can be calculated from the worn crater volume, which in turn can be easily derived from the crater diameter.

In the case of combined wear of a coating and substrate, it was shown that the following relationship exists [1]:

$$\frac{S.N}{D^4} = \left( \frac{K_c - K_s}{K_c \cdot K_s} \right) \left( \frac{\pi}{64R} - \frac{\pi.t}{4D^2} + \frac{\pi.R.t^2}{D^4} \right) + \left( \frac{1}{K_c} \right) \left( \frac{\pi}{64R} \right) \quad (1)$$

where S is the sliding distance, N is the contact force, t is the coating thickness, D is the external diameter of the wear crater, and K is the wear factor, where the subscripts s and c refer to the substrate and the coating, respectively.

Thus a plot of  $\frac{S.N}{D^4}$  against  $\frac{\pi}{64R} - \frac{\pi.t}{4D^2} + \frac{\pi.R.t^2}{D^4}$  should be linear with the intercept and gradient determined by the values of  $K_s$  and  $K_c$ .  $K_c$  can be determined directly from the intercept, and this value then used together with the gradient to provide  $K_s$ . A typical linear fit through such data is shown in fig. 2. It can be seen that the data scatter considerably, which raises doubts on the quality of the fit.

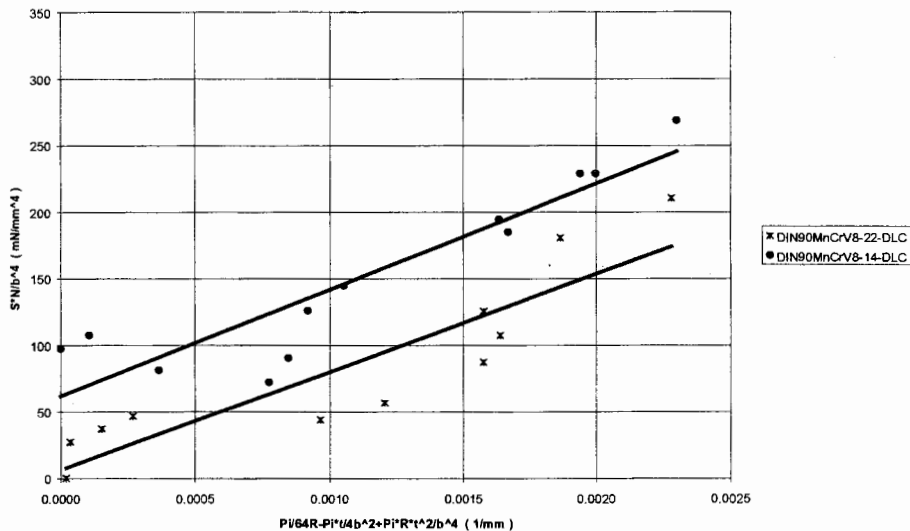


Figure 2: Typical data to determine the coating and substrate wear in a combined measurement.

As abrasive suspensions, a commercial diamond slurry of unknown standard concentration (Streurs code SAPNO P) with 1  $\mu$ m diameter particles as well as a suspension of F 1200 SiC abrasive powder in distilled water (35 g in 100 ml) were used. The particle size distribution in the SiC/H<sub>2</sub>O suspension was measured by laser granulometry which revealed that the average particle grain size was 6  $\mu$ m (10% < 4.15  $\mu$ m; 90% < 9.9  $\mu$ m). The drip feed rate was set at approx. 15 drops/min. and 150 drops/min. for the diamond and SiC suspensions, resp. It was checked that under these conditions a stable test regime was obtained.

A new ball bearing, grade 48 according to standard AFBMA 10-1983 - USA, of hardened DIN 100Cr6 (AISI 52100) steel and 25 mm in diameter was used for each experiment. The crater diameters were measured with a reflected light microscope at a magnification of 4X, using a graticule with a resolution of 25  $\mu$ m.

## Results

### 1) Less wear for higher contact loads

Fig. 3 shows the effect of the applied contact load on the wear rate of a hardened high speed steel (AISI M2) polished, uncoated specimen. An effect of the normal load may be expected,

but surprisingly the wear is reduced for increasing loads. The corresponding wear factors ranged from  $2.2 \cdot 10^{-13}$  to  $3 \cdot 10^{-15}$   $\text{m}^2/\text{N}$ , for contact loads of 0.1 N to 2 N.

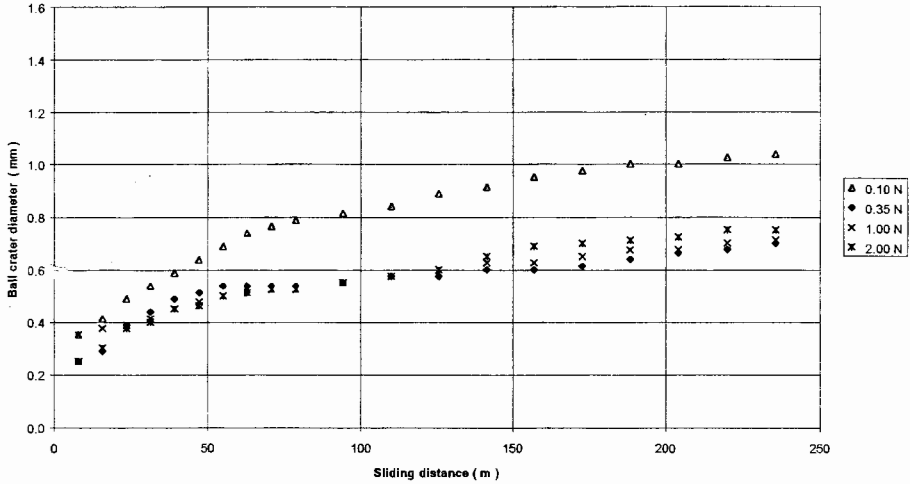


Figure 3: Influence of the contact load on the crater dimensions in a AISI M2 bare steel specimen (ball rotational speed: 126 rpm, abrasive medium: diamond suspension).

## 2) A significant influence of the ball rotational speed

When reducing the ball rotational speed from 150 rpm to 50 rpm on a DLC coated AISI M2 steel specimen, it was observed that the wear rate increased significantly (fig. 4). The corresponding wear coefficient of the DLC coating increased from  $1.2$  to  $2.8 \cdot 10^{-14}$   $\text{m}^2/\text{N}$ .

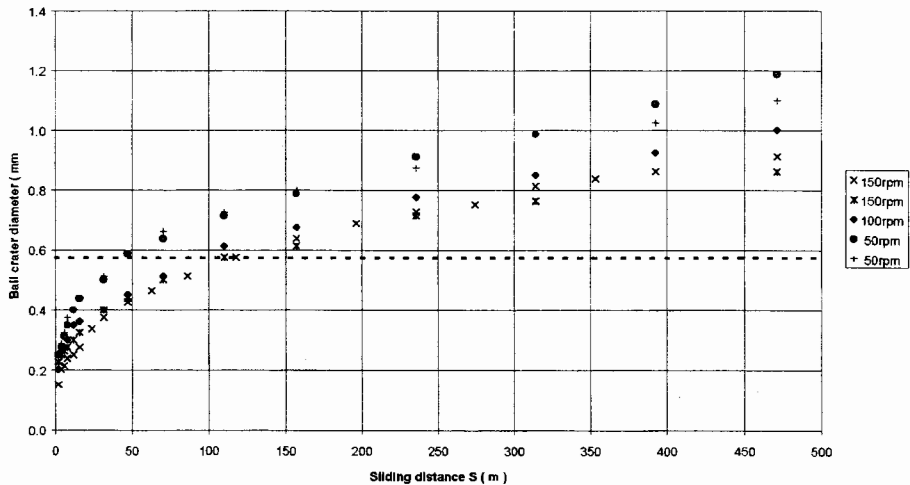


Figure 4: Influence of the ball rotational speed on the crater dimensions in a DLC coated AISI M2 steel substrate (contact load: 0.35 N, abrasive medium: diamond suspension). The dashed line indicates where the coating is perforated.

### 3) Enhanced abrasive wear with softer particles

The use of the two different abrasive media resulted in considerable differences in the wear rate of uncoated bare steel specimens as well as coated samples. Fig. 5 shows the results for a hardened uncoated AISI M2 substrate, while fig. 6 shows the result for a DLC coated AISI M2 specimen.

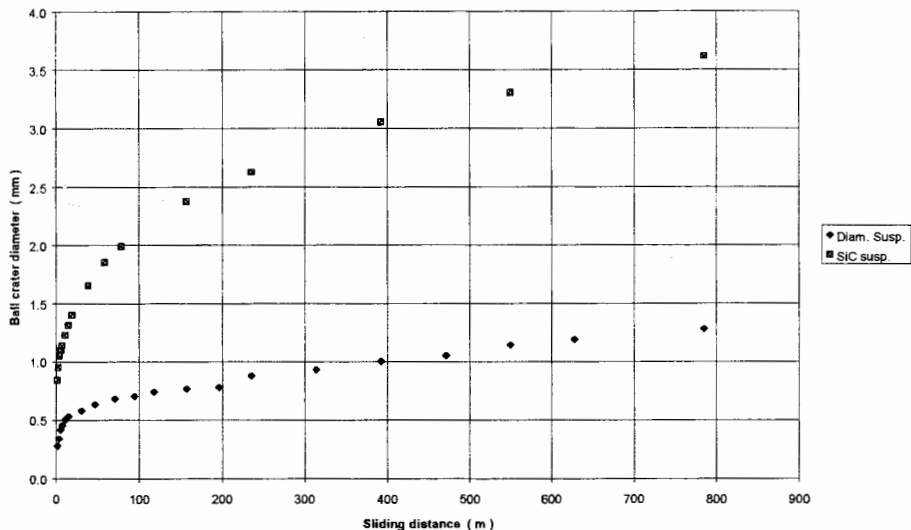


Figure 5: Influence of the abrasive medium on the wear rate of a hardened uncoated AISI M2 specimen. (contact load: 1 N, ball rotational speed: 126 rpm).

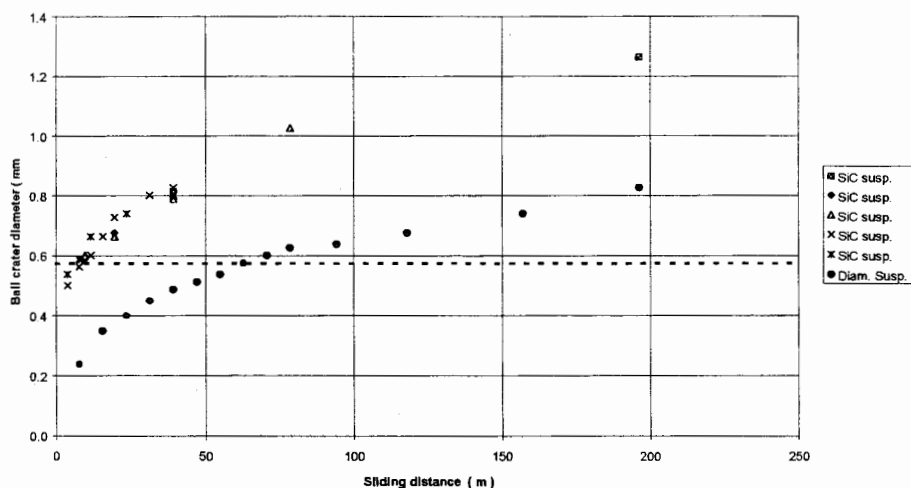


Figure 6: Influence of the abrasive medium on the wear rate of a hardened DLC coated AISI M2 specimen. (contact load: 0.25 N, ball rotational speed: 126 rpm). The dashed line indicates where the coating is perforated.

In both cases, the SiC/water suspension produced more wear compared to the diamond abrasive suspension. This may be attributed to the bigger grain size of the SiC particles, since their hardness is lower than that of diamond particles. The corresponding wear factor of the steel sample varied between  $8.5 \cdot 10^{-13} \text{ m}^2/\text{N}$  to  $9 \cdot 10^{-15} \text{ m}^2/\text{N}$ , while that of the DLC coating varied between  $2 \cdot 10^{-13} \text{ m}^2/\text{N}$  to  $2.2 \cdot 10^{-14} \text{ m}^2/\text{N}$ , for SiC and diamond suspensions, respectively.

#### 4) Softer materials yield a better abrasion resistance

In table 1, wear coefficients of ball crater experiments in uncoated and DLC coated cold work tool steel samples, hardened and tempered to different hardness values, are shown. The designation 'coating only craters' refers to measurements derived from shallow ball craters restricted to within the coating thickness. The 'combined measurements' refer to through-thickness ball craters where eq. (1) was used to derive wear factors for the coating and the substrate. The corresponding wear curves are depicted in figure 7, and pictures of the craters in the specimens after 10 000 ball revolutions are displayed in fig. 8.

Table 1: Wear coefficients obtained by ball cratering (unit:  $10^{-15} \text{ m}^2/\text{N}$ ) on uncoated and DLC coated DIN WN 1.2842 steel specimens of different hardness.

Sample	Substrate hardness	bare steel specimens	coating only craters	combined measurements	
steel code	HRC	$K_s$	$K_c$	$K_s$	$K_c$
DIN90MnCrV8	$10.3 \pm 3.7$	$3.0 \pm 0.3$	$45 \pm 9$	$11.6 \pm 1.0$	$76 \pm 15$
DIN90MnCrV8	$31.5 \pm 1.3$	$4.3 \pm 0.3$	$20 \pm 22$	$-19 \pm 58$	$56 \pm 39$
DIN90MnCrV8	$61.2 \pm 1.0$	$11.5 \pm 0.9$	$38 \pm 16$	$-35 \pm 13$	$34 \pm 13$

Reported errors are standard deviations of three measurements.

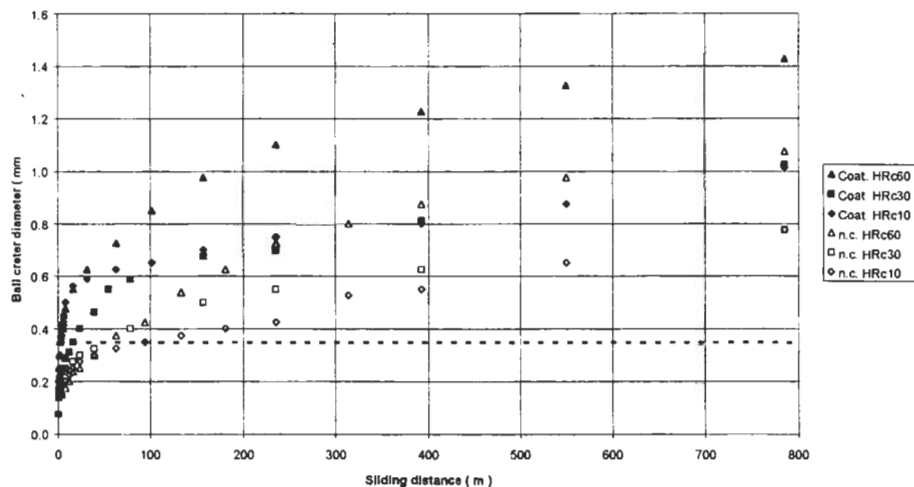
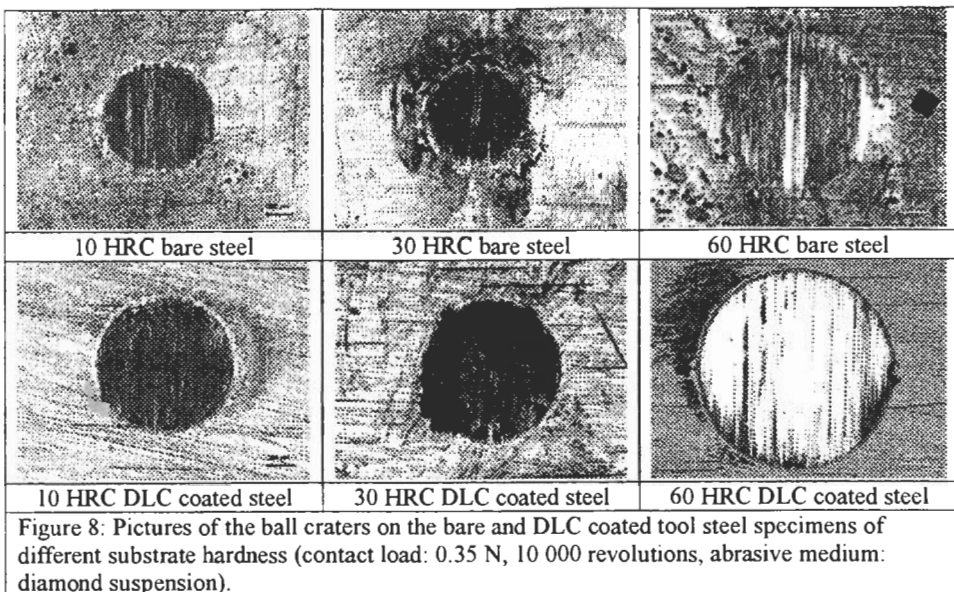


Figure 7: Influence of the substrate hardness on the wear rate of bare and DLC coated tool steel specimens of different substrate hardness (contact load: 0.35 N, ball rotational speed: 150 rpm, abrasive medium: diamond suspension). The dashed line indicates where the coating is perforated.



The harder bare steel samples yield higher wear factors and hence poorer abrasion resistance, which is quite surprising since the abrasive wear resistance of a material is usually conferred by its hardness [2]. The hard DLC coating (18 GPa as measured by nano-indentation) apparently results in increased abrasive wear of the surface, compared to the uncoated specimens. Anomalous, sometimes negative wear factors for the substrate are obtained when values are derived from through-thickness craters using eq (1). The wear factors for the DLC coating scatter considerably.

## Conclusions

Clearly, the results of the apparently simple ball crater abrasion test quite often confront the inexperienced user with puzzled minds. Issues that may be considered to explain the unexpected results are:

- The influence of the fluid film thickness (proportional to the square of the sliding speed), reducing the load borne by the abrasive particles, and the conditions under which abrasive particles can be entrained in the contact [3]. However, the parameters necessary in these calculations are often difficult to determine and the assumptions sometimes unrealistic.
- Deviations from perfect spherical wear craters, possibly by the wearing of the ball during the test, resulting in inaccurate wear volume measurements [4].
- The influence of the specimen hardness related to that of the rigid hardened tool steel counterbody backing of the abrading particles. A hard specimen may for example lead to fracture of the abrasive, resulting in a transition from mild wear to severe wear [5].
- The influence of wear debris during the measurement, in particular for hard coatings on metallic substrates.

Despite of these difficulties, it is still believed that the ball crater test for determining the abrasion resistance of materials shows much potential both as a research tool and for the quality control of components. However, research is needed to determine the reproducibility

of the test and the sensitivity to the various test parameters, to develop this new technique into a robust method of test yielding reliable results on the workfloor.

## References

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