# Slide diamond burnishing of tool steels with adhesive coatings and diffusion layers

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We have performed surface modification of selected tool steels. The steels were covered with adhesive coatings of the hard chrome type or with diffusion layers of the nitride type. We have investigated in particular surface roughness, since it is known to affect friction, lubrication and wear. We have also considered an accumulation of strain energy in the strained area, which accompanies the crystal lattice deformation caused by burnishing. Surface roughness was determined by a profilometer before and after burnishing. Adhesion of coatings to steel was determined with a scratch tester. A combination of both approaches, slide burnishing with hard chrome coating and/or slide burnishing with nitriding, seems worthwhile. Both treatments and their combinations can be used in manufacturing tools and structural elements in automotive and aerospace industries.

**Keywords:** Tool steels, Slide diamond burnishing, Surface roughness, Nitriding, Chromium plating

## Introduction

Mechanical preparation of the surfaces of steel machine parts is an important function before the deposition of an anticorrosion or antiwear adhesive or a diffusion coating. The processes of brush cleaning, sand blasting, peening and shot peening are appropriate means for removal of surface mechanical impurities in surface preparation of machine components for adhesive or diffusion coating.

The strength of coatings deposited on surfaces so prepared is high. However, one wonders whether removal of impurities is the only effect of the cleaning. Surfaces, which have been mechanically cleaned but not immediately coated, react very quickly with the environment: layers of oxides, sulphides, etc., inhibit a later coating process. It is known that mechanically cleaned parts undergo compressive surface deformation accompanied by compressive internal stresses.

The stresses induced in the surface layer increase the surface energy of the crystal lattice.[1] In turn, this increases chemical reactivity and might facilitate subsequent coating of steel components by both adhesive and diffusion processes.

Mechanical processes of surface preparation unfortunately do not guarantee the attainment of high surface finish after coating. Thus, we have a potential for improvement in properties of adhesive or diffusion deposited coatings by strain and compressive stress introduced in slide or roller burnishings. Such treatments can provide higher surface smoothness not attained by typical mechanical means of surface preparation of components to be coated. This situation provides the starting point of the present work.

We have applied diamond slide burnishing as a process preceding galvanic (chromium plating) or diffusion (nitriding) treatment. Thus, our approach is an alternative to the extant methods of surface preparation before chromium plating or nitriding such as grinding, polishing and other abrasive treatments.[2–6]

## Earlier work

The burnishing process has an extensive history.[1–3,7–10] On the other hand, there is literature on application of nitride and galvanic hard chromium coatings and the resulting effects on mechanical and tribological resistance of the coated elements.[5,11–13] There have been attempts to apply burnishing as a remedy for the detrimental effect of tensile stresses remaining in galvanic coatings.[12,13] Combined methods have been also applied, such as burnishing with plasma or laser action to facilitate formation of resistant layers on the processed surfaces.[14–16] However, little effort has been expended so far in applying the following combination: burnishing plus diffusion or adhesive coating.[11,15]

## Materials selection

Two chromium plus vanadium plus molybdenum powder metallurgy tool steels were chosen: Vanadis 6 (2·10 wt-%C, 6·8%Cr, 0·4%Mn, 1·5%Mo, 1·0%Si, 5·4%V) and Vanadis 10 (2·90%C, 8·0%Cr, 0·5%Mn, 1·5%Mo, 0·5%Si, 9·8%V). They are widely applied for

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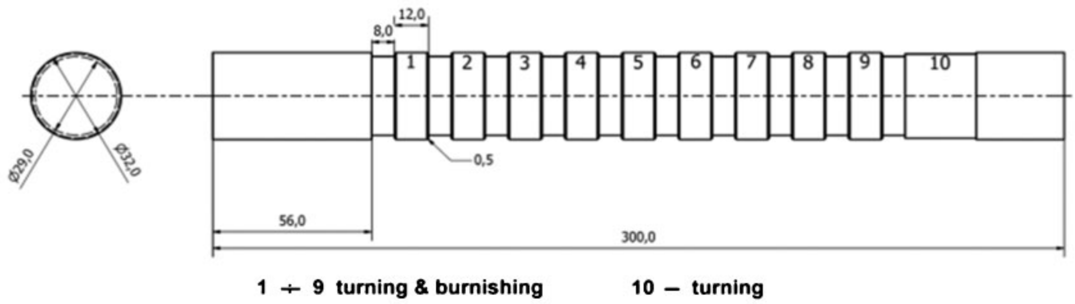



1 Sample bar view (samples 1–10)

cold working tools. Those steels are commonly coated with galvanic hard chromium deposits or subjected to nitride bath hardening.

Shortcomings of adhesive hard chromium coatings are related to their poor mechanical and tribological properties, a consequence of tensile residual stresses.[5,15] Moreover, there is poor adhesion of the coating to the metal substrate. Burnishing might be a way to mitigate these problems.[2,3,13] Tensile stresses can be approximately compensated by compressive stresses formed in the upper layer of the chromium coating. Nitride diffusive layers also pose problems: insufficient hardening of the surface, irregular nitrogen penetration into the upper layer and too large gradient of work hardening resulting in inadequate mechanical properties of the layer.[17]

## Experimental

Slide burnishing of our tool steels in the quenched state was carried out using diamond tools produced by the Institute of Advanced Manufacturing Technology (IAMT). The ball end of the burnishing tool had a radius $R=1{\cdot}5$ mm and was produced from a synthetic polycrystalline diamond. That diamond was a composite containing diamond grains and a titanium–silicon carbide ceramic bonding phase, $Ti_3SiC_2$.[18,19]

The experiments were carried out on a Mori Seiki NL2000SY CNC turning–milling centre, numerically controlled along five axes. The burnishing tool was fixed to the cutting head by means of a special fixture, which ensured the possibility of elastic clamping. The clamping force was recorded.

Predefined factors were as follows: type of initial treatment, the number of burnishing passes $i$, the type of lubricant, the burnishing speed $v$ and roughness described by several parameters. These parameters have been defined by the ISO standard called EN ISO 4287:1998. They pertain to the real surface and to the surface profile. The real surface is defined as limiting the body and separating it from the surrounding medium. The surface profile results from the intersection of the real profile by a specified plane along the $X$ axis (one uses the standard Cartesian coordinates, the $Z$ axis is perpendicular to the $X$–$Y$ plane). The roughness parameters include $R_a$ (the arithmetical mean deviation of the assessed profile from the plane), $R_z$ (10-point height of the profile) and $R_{mr}$ (also called the relative material ratio, which is the ratio of the material length of the profile elements at a given level with respect to the $X$–$Y$ plane to the evaluation length). Profilograms of the surface roughness were recorded.

Longitudinal turning of the bar probe (Fig. 1) with a tool insert holder was performed first. Turning improves the surface geometry, thus affecting the roughness. The roughness $R_a$ of the surface after turning but before burnishing was $\sim 1$ μm for samples 6·1, 6·2 and 10·1; the value was $\sim 0{\cdot}70$ μm for sample 10·2. We applied each time only one burnishing pass; hence, $i=1$. An oil mist made from the Castrol Hysol oil was applied during burnishing.

The speed of burnishing maintained throughout the experiments was $v=30$ m min$^{-1}$. According to the literature[2,3,7,8,13] and our own results, the speed does not significantly affect burnishing results in a wide range of values. The value of $v$ that we have selected did not cause self-excited vibrations during the burnishing.

Vickers microhardness $h_{\mathrm{Vickers}}$ was determined using an FM 7 tester from Future Tech. Corp., Japan. Microindentations were made using a 200 g load.

We have used a JEOL JSM 6460 V digital scanning electron microscope equipped with an energy dispersive X-ray spectrometer.

Changes in the diameter of the shaft before and after burnishing $\Delta d$ were measured. The magnitude of the plastic deformation of the material is widely assumed to be equal to $\Delta d/2$. We have

$$\Delta d = |d' - d| \quad (1)$$

where $d'$ is the diameter of the shaft before burnishing and $d$ afterwards.

We have also calculated the index of the roughness change as

$$K_{R_a} = R'_a / R_a \quad (2)$$

where $R'_a$ is the value before burnishing and $R_a$ afterwards.

Still, further, we have determined the index of unevenness of deformation as

$$K_z = \Delta d / 2R_z \quad (3)$$

whereas before the index pertains to the value before burnishing.

After burnishing and successive scouring processes, surfaces were immediately galvanised or nitrogenised under typical conditions defined in Tables 1 and 2.

There is a variety of metal deposition techniques, often aimed at providing wear resistance and corrosion resistance or at rebuilding worn and/or corroded parts back to their dimensional tolerances.[20–22] The process we have used is an electrolytic one, with the object placed in a bath for 3 h; composition of the bath and other parameters are provided in Table 1.

**Table 1 Parameters and composition of bath for chrome plating**

| Components of bath | Process temperature/°C | Current density/A dm$^{-2}$ |
|---|---|---|
| $H_2SO_4$ (sulphuric acid)<br>$CrO_3$ (chromium oxide) | 55–57 | 30 |

The nitriding process that we have applied is a surface hardening heat treatment that introduces nitrogen into the material surface. It can be carried out using gaseous, liquid or solid medium.[23] We have applied gas nitriding carried out with ammonia gas, which dissociates on the surface of the steel. The resulting atomic nitrogen is absorbed by the surface. While nitriding may be either a single or double stage process, we have applied the latter, also known as the Floe process.[24] Parameters of the process are listed in Table 2. In the two stage method, it is frequently possible to meet dimensional tolerances without a final grinding operation.[25] Since the $NH_3$ content of the atmosphere is reduced, the iron nitride does not grow rapidly and in fact dissolves as it supplies nitrogen into the interior of the steel. Nitriding times are quite long, anywhere from 10 to 130 h depending on the application.[24]

Scratch resistance of galvanised bars was determined using a Revetest Scratch Tester (CSM Instruments, Peseux, Switzerland). The use of this technique has been described among others in review articles.[26,27] We have also used a machine called Calotester developed at IAMT, which was applied to determine the coating thickness by grinding a spherical indentation followed by a microscopic examination of the resultant crater according to ISO 26423:2009.

Afterwards, selected sections of bars were cut. A wire cutting machine (EWEB 40CNC, EDM, Cracow, Poland) was used, and no significant changes to the upper layer were seen. Every separated section was later prepared for scanning electron microscopy and microhardness examination.

Our objectives required identification of the effect of the technical parameters of diamond slide burnishing on the quality of the product. Here, the product is the surface of the component to be further treated by depositing a galvanic coating (chromium plating) or diffusion coating (nitriding). We studied parameters characterising the surface layer (roughness, hardening and internal stresses) from the point of view of quality of the subsequently deposited coatings as well as their adhesion to the substrate.

**Table 2 Nitriding process parameters**

| Stage | Process temperature/°C | Time/h |
|---|---|---|
| First stage | 520 | 5 |
| Second stage | 535 | 20 |

## Results

Values of $\Delta d$, $K_z$ and $K_{R_a}$ so obtained are provided in Tables 3 and 4. Burnishing feed $f$ and force $F$ were determined as before.[7–9] They are the most important technological parameters of slide burnishing with the elastic clamping limiting the quality of surface. Values of these parameters depend on the workpiece material.

Determination of the optimum values of clamping force tool requires the knowledge of three-dimensional surface parameters (stereometry parameters) of machined surface, dimensions of the tool and workpiece, and mechanical properties of the material.

There are a number of simplified empirical formulae allowing for the determination of burnishing force at slide diamond burnishing.

Determination of the size of the axial feed f requires an analysis of burnishing conditions. The shape and burnisher end radius are among the main factors that allow to determine the value of feed used in the course of burnishing. The geometric structure of the surface after turning and before burnishing is pertinent also.

We provide below a selected profilogram after turning in Fig. 2*a* and for the same material after burnishing in Fig. 2*b*. Other such diagrams have been omitted for brevity.

Comparing Fig. 2*a* and *b*, we see a change in the character of the surface. The structure seen in Fig. 2*b* has been sometimes called 'mixed'.[28]

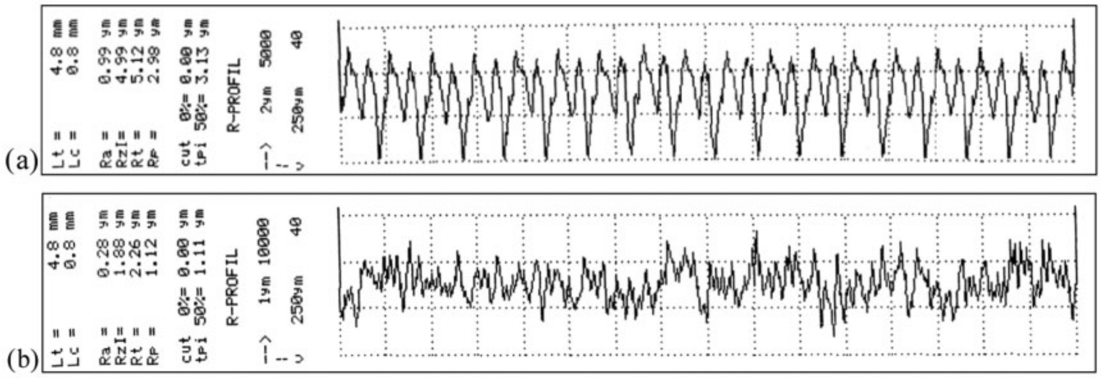
Further information on surfaces is provided in Figs. 3 and 4. Figure 3 shows good agreement of results observed for our two steels. Surface roughness improvement as represented by $K_{R_a}$ goes up at higher values of the burnishing force applied. Still higher values than we have used are not worthwhile for steels we have studied since damage to the upper layers is possible.

In contrast to $K_{R_a}$, our two steels behave differently when we follow the deformability index $K_z$ as a function of the force $F$ in Fig. 4. Several factors could have

**Table 3 Test results of Vanadis 6 (61 HRC) slide burnishing**

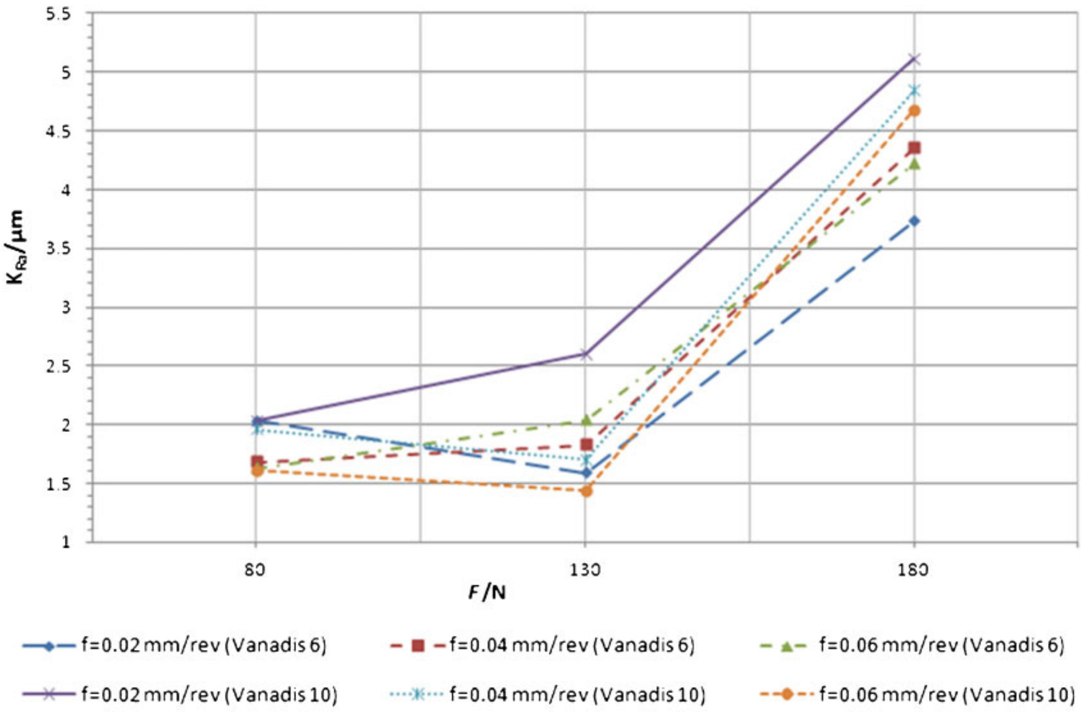
| Test no. | Burnishing force $F$/N | Feed $f$/mm rev$^{-1}$ | SG parameters after turning | | | | SG parameters after burnishing | | | | Diameter change $\Delta d$/μm | $K_{R_a}$ | $K_z$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $R'_a$/μm | $R'_z$/μm | $R'_t$/μm | $R_{mr}$/μm | $R_a$/μm | $R_z$/μm | $R_t$/μm | $R_{mr}$/μm | | | |
| 1 | 80 | 0·02 | 1·01 | 5·07 | 5·15 | 3·13 | 0·41 | 3·11 | 3·47 | 1·80 | 0 | 2·49 | 0·00 |
| 2 | 80 | 0·04 | 0·99 | 5·00 | 5·23 | 3·10 | 0·37 | 2·89 | 3·26 | 1·17 | 1 | 2·68 | 0·10 |
| 3 | 80 | 0·06 | 0·97 | 4·77 | 4·85 | 2·97 | 0·36 | 2·34 | 2·56 | 1·00 | 3 | 2·69 | 0·31 |
| 4 | 130 | 0·02 | 0·99 | 4·87 | 4·95 | 3·03 | 0·27 | 2·01 | 2·29 | 1·13 | 4 | 3·71 | 0·41 |
| 5 | 130 | 0·04 | 0·97 | 4·71 | 4·83 | 2·90 | 0·26 | 1·65 | 1·83 | 0·80 | 5 | 3·73 | 0·53 |
| 6 | 130 | 0·06 | 0·88 | 4·83 | 5·00 | 2·83 | 0·27 | 1·83 | 2·11 | 0·90 | 5 | 3·25 | 0·52 |
| 7 | 180 | 0·02 | 0·97 | 5·21 | 5·13 | 3·53 | 0·18 | 1·48 | 1·60 | 0·73 | 2 | 5·29 | 0·19 |
| 8 | 180 | 0·04 | 0·96 | 4·93 | 5·18 | 3·30 | 0·26 | 1·76 | 1·91 | 0·87 | 2 | 3·66 | 0·20 |
| 9 | 180 | 0·06 | 0·92 | 4·65 | 4·76 | 2·93 | 0·37 | 2·50 | 2·72 | 1·00 | 6 | 2·46 | 0·65 |
| Turning | | | 0·12 | 0·71 | 0·79 | | | | | | | | |

*SG: surface geometry.




*a* after turning before burnishing (burnishing tool NKD-1 with $R$=1·5 mm, force $F$=130 N, feed $f$=0·06 mm rev$^{-1}$); *b* after burnishing

**2 Profilograms of surface roughness for specimen of Vanadis 6 steel**

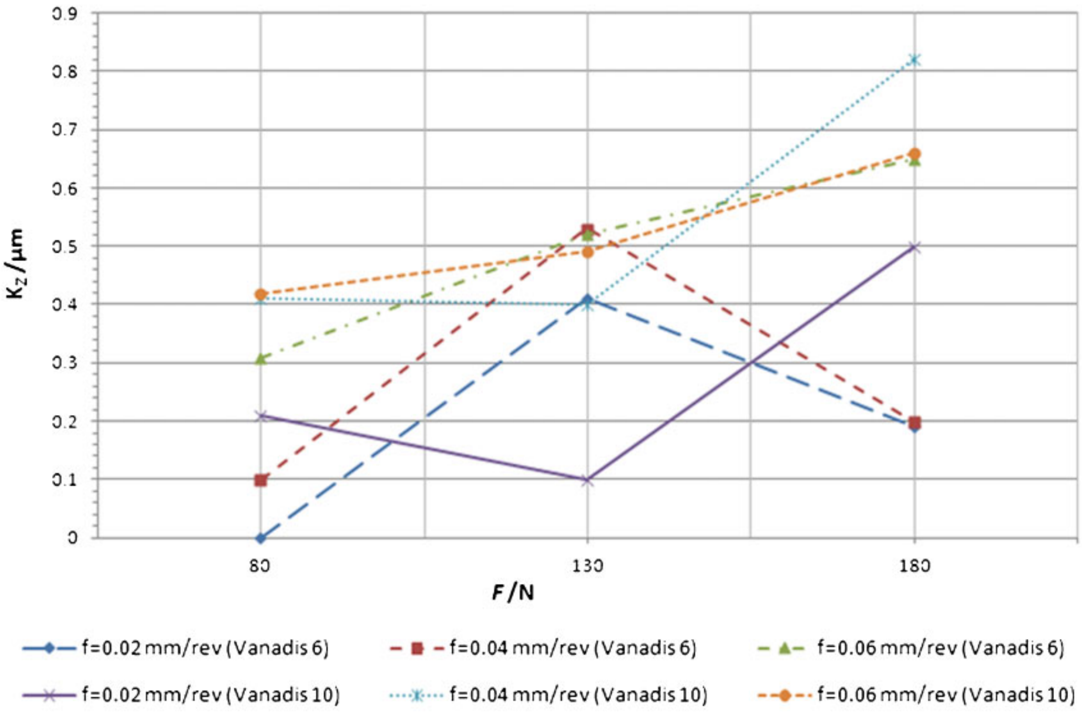



**3** $K_{R_a}$ **as function of force** ***F***

**Table 4 Test results for Vanadis 10 (61 HRC) slide burnishing**

| | | | SG parameters after turning | | | | SG parameters after burnishing | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Test no. | Burnishing force $F$/N | Feed $f$/mm rev$^{-1}$ | $R'_a$/µm | $R'_z$/µm | $R'_t$/µm | $R_{mr}$/µm | $R_a$/µm | $R_z$/µm | $R_t$/µm | $R_{mr}$/µm | Diameter change $\Delta d$/µm | $K_{R_a}$ | $K_z$ |
| 1 | 80 | 0·02 | 0·94 | 4·73 | 4·81 | 2·43 | 0·54 | 3·27 | 3·42 | 1·03 | 2 | 1·72 | 0·21 |
| 2 | 80 | 0·04 | 0·96 | 4·84 | 4·94 | 2·57 | 0·48 | 3·32 | 3·65 | 1·40 | 4 | 2·01 | 0·41 |
| 3 | 80 | 0·06 | 0·98 | 4·74 | 4·83 | 2·60 | 0·50 | 3·43 | 3·71 | 1·37 | 4 | 1·95 | 0·42 |
| 4 | 130 | 0·02 | 1·0 | 4·99 | 5·13 | 2·80 | 0·47 | 3·29 | 3·49 | 1·60 | 1 | 2·11 | 0·10 |
| 5 | 130 | 0·04 | 0·94 | 4·96 | 5·07 | 2·70 | 0·43 | 2·93 | 3·21 | 1·47 | 4 | 2·18 | 0·40 |
| 6 | 130 | 0·06 | 0·97 | 5·05 | 5·15 | 2·83 | 0·47 | 3·18 | 3·34 | 1·27 | 5 | 2·06 | 0·49 |
| 7 | 180 | 0·02 | 0·87 | 4·96 | 5·31 | 3·00 | 0·57 | 3·59 | 4·01 | 1·77 | 5 | 1·54 | 0·50 |
| 8 | 180 | 0·04 | 0·90 | 4·89 | 4·86 | 2·67 | 0·21 | 1·79 | 2·41 | 1·17 | 8 | 4·23 | 0·82 |
| 9 | 180 | 0·06 | 0·87 | 4·56 | 4·69 | 2·43 | 0·32 | 2·21 | 2·35 | 0·63 | 6 | 2·74 | 0·66 |
| Turning | | | 0·14 | 0·78 | 0·83 | | | | | | | | |

*SG: surface geometry.




**4 $K_z$ as function of force $F$**

**Table 5 Adhesion test results for galvanic hard chromium coatings deposited on cylindrical surfaces of Vanadis 6 specimen after turning process and turning and burnishing process**

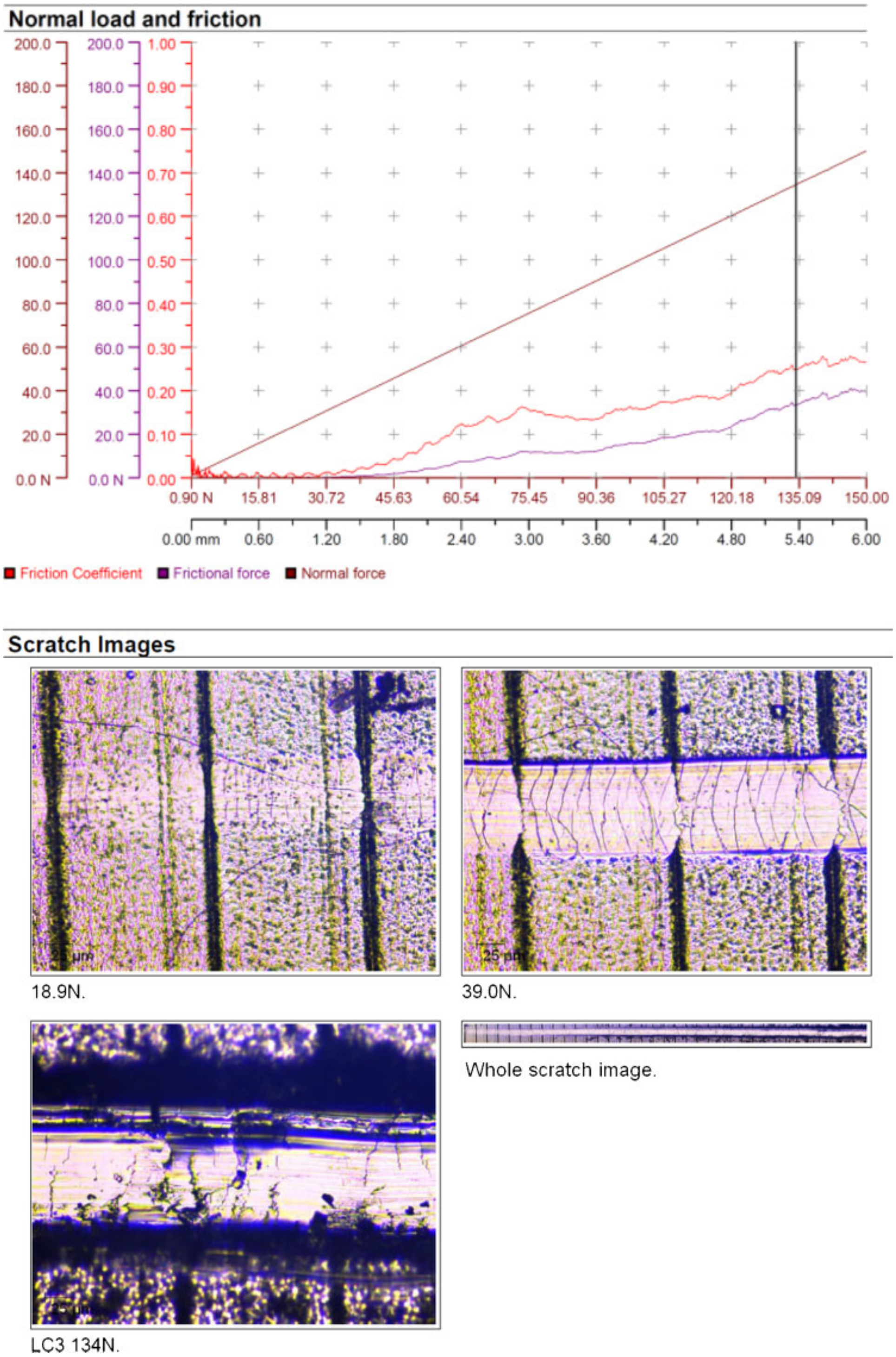
| | | | Values of normal force breaking coating/N | | | |
|---|---|---|---|---|---|---|
| Test no.* | Burnishing force $F$/N | Feed $f$/mm rev$^{-1}$ | Individual | Average | Standard deviation | Confidence interval for $\alpha$=0·10 |
| 6 | 130 | 0·06 | 58<br>60<br>56 | 58 | 2·2 | 3·7 |
| 7 | 180 | 0·02 | 57<br>58<br>56 | 57 | 0·8 | 1·4 |
| 8 | 180 | 0·04 | 62<br>65<br>64. | 64 | 1·5 | 2·5 |
| 10 | | | 87<br>92<br>98 | 92 | 5·1 | 8·6 |

*Samples 6–8: turned and burnished; sample 10: turned only.

**Table 6 Adhesion test results for galvanic hard chromium coatings deposited on cylindrical surfaces of Vanadis 10 specimen after turning process and turning and burnishing process**

| | | | Values of normal force breaking the coating/N | | | |
|---|---|---|---|---|---|---|
| Test no.* | Burnishing force $F$/N | Feed $f$/mm rev$^{-1}$ | Individual | Average | Standard deviation | Confidence interval for $\alpha$=0·10 |
| 7 | 180 | 0·02 | 110<br>116<br>122 | 116 | 5·8 | 9·7 |
| 8 | 180 | 0·04 | 121<br>129<br>114 | 121 | 7·3 | 12·3 |
| 9 | 180 | 0·06 | 116<br>131<br>134 | 127 | 9·5 | 16·1 |
| 10 | | | 121<br>...<br>119 | 120 | 1·7 | ... |

*Samples 7–9: turned and burnished; sample 10: turned.

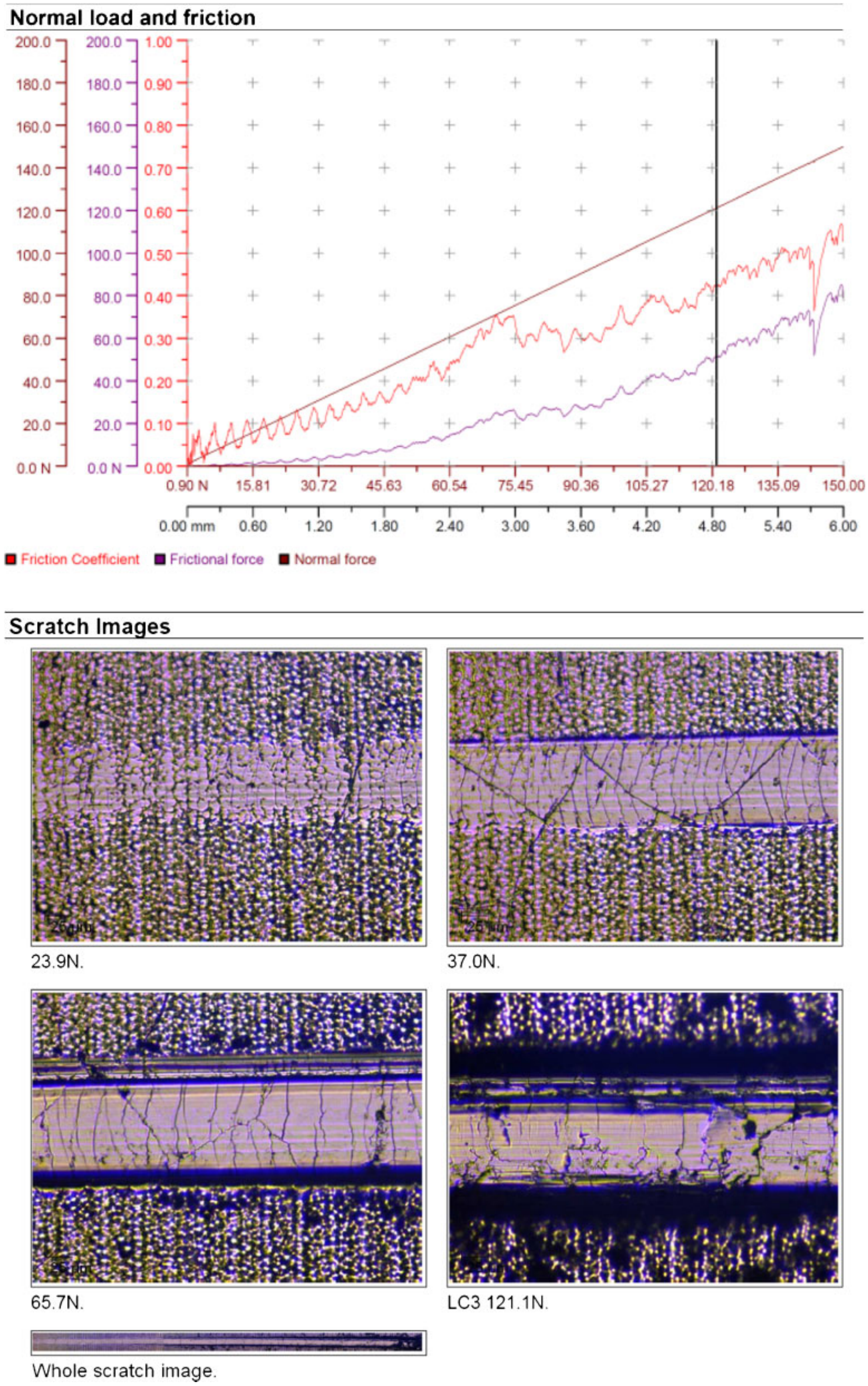



**5 Scratch images at different loads and scratch testing diagram for hard chromium coating on cylindrical surface of Vanadis 10 steel (sample 9, surface turned and burnished before coating deposition)**

influenced the behaviour observed, including friction and adhesion. This relationship deserves a further study.

The scratch resistance of the burnished and coated surfaces has been determined according to the EN 1071-3:2007 standard. Values of normal force breaking the coating on the surface, which were turned as well as turned and burnished before coating deposition, are given in Tables 5 and 6. Some selected charts and scratch surface photographs are presented in Figs. 5 and 6.

In the case of Vanadis 10 steel sample, which was turned and burnished varying parameters before the coating deposition, the values of the normal force fracturing the coating were from 110 to 134 N. The coating deposited on the surface after a turning operation shows the level of adhesion corresponding to the range of critical loads from 119 to 121 N. These results demonstrate a beneficial effect of burnishing on hard chromium coating adhesion. Moreover, the burnishing process generates high level of compressive stresses in the deformed surface layer. We have used the following parameters for sample 9: burnishing force, 180 N; feed 0·06 mm rev$^{-1}$. In this case, the mean value



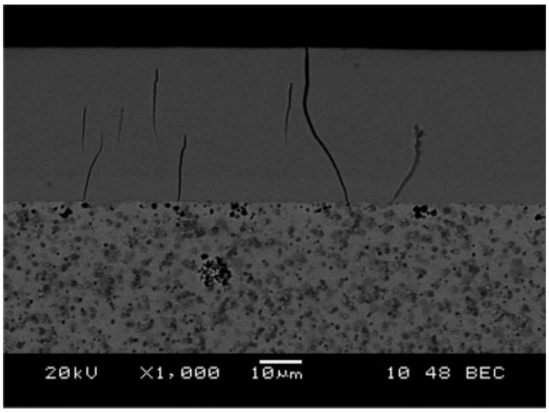

**6 Scratched surface images at different loads and scratch testing diagram for hard chromium coating on cylindrical surface of Vanadis 10 steel (sample 10, surface turned before coating deposition)**

of the normal force breaking the coating was 127 N, while in case of the surface that was only turned before coating deposition, the value was 120 N (sample 10). The scratch resistance increase was thus 5·5%.

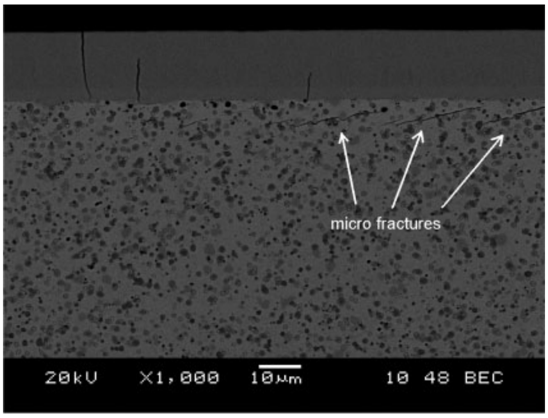
In turn, we now consider observations of the coated steels under a scanning electron microscope as displayed in Figs. 7 and 8. We find that the number of microfractures of coatings goes down to approximately one-half when our burnishing process has been applied (Fig. 8).

Because of the brittle nature of the microfractures and the kind of stresses applied, all microfractures are perpendicular to the surfaces of the specimens.

We have found that with small nose radii $R$ of the burnisher and high burnishing forces, it is easy to exceed the limit of the surface strength and create several




7 **Images of microfractures formed in galvanic coating as result of tensile stresses at surface of Vanadis 6 specimen (sample 10, surface turned before coating deposition)**




8 **Image of microfractures formed in Vanadis 6 specimen resulting from tensile stresses (sample 7, surface turned and burnished before coating deposition)**

microfractures parallel to the burnished surface (Fig. 8). The result would be peeling off the coating just at the beginning of its service.

We have determined the Vickers microhardness $h_{\mathrm{Vickers}}$, a quantity we have used before to characterise other types of materials and coatings.[29] In the case of nitrogenised surfaces of Vanadis steels, we observe a significant increment of the microhardness (Fig. 9). The increment amounts to 10% for burnished surfaces as compared to surfaces nitrided only. The thickness of the upper layer has also increased in the burnishing process, from ~180 to 330 μm.

A simple comparison of the microhardness versus distances from the treated surface (Figs. 9 and 10) shows higher values for the hybrid treatment (burnishing plus nitriding).

## Survey of results

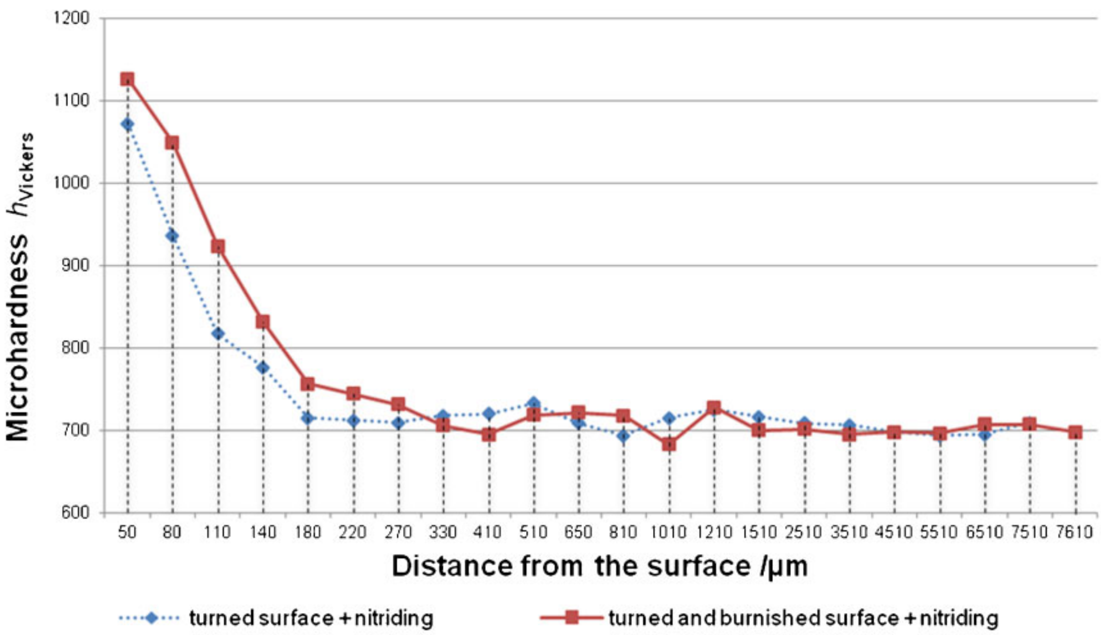
We have demonstrated that burnishing is an alternative method of surface finishing for Vanadis 6 and 10 steels. Burnishing can improve $K_{R_a}$ and $K_z$ parameters discussed above, the former more than fivefold.

The burnishing operation requires a small nose radio of the tool (1·5 mm) and a relatively high burnishing pressure. At the same time, a high burnishing pressure might damage the tool, so caution is advised.

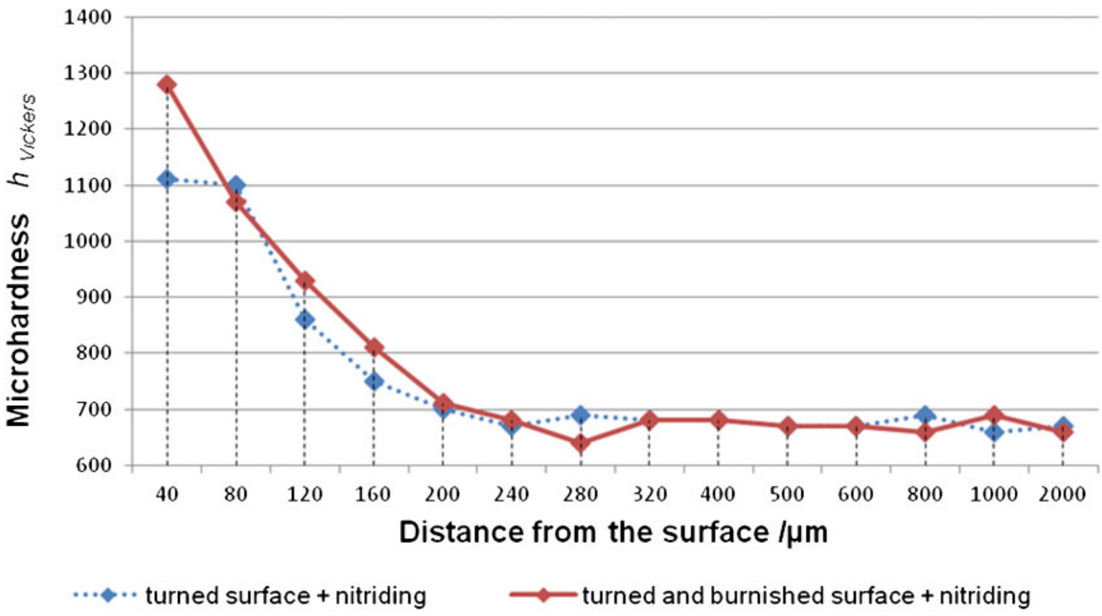
Burnishing as an operation preceding coating formation provides good results. In the case of Vanadis 6, we have a 10% increase in the Vickers hardness, an 80% increase in the thickness of the nitride layer and a lower gradient of workhardening.

Burnishing as a precedent operation also improves properties of hard chromium galvanic coatings. In particular, the scratch resistance is improved.

Comparison of the chromium coating and nitriding stages of the reinforcement process is difficult since time scales are different. As discussed in the section on 'Experimental', nitriding times are quite long, between 10 and 130 h.




9 **Microhardness of Vanadis 6 specimens after turning, slide diamond burnishing and nitriding**




**10 Microhardness of Vanadis 10 specimens after turning, slide diamond burnishing and nitriding**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