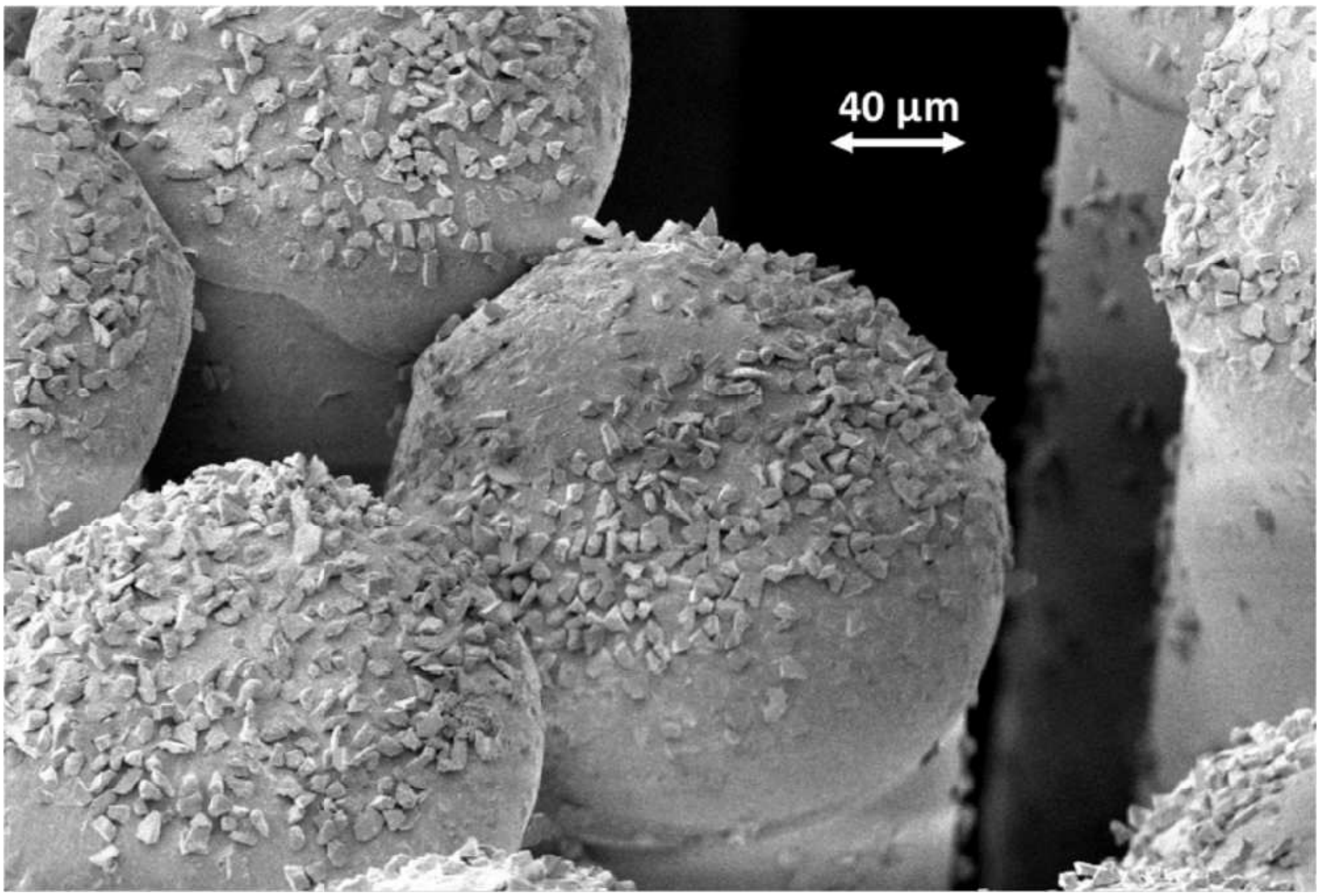
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A new generation of highly flexible and soft tools for high precision surface finishing with embedded micro-diamonds

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Abstract. Fully automated and process-integrated, high-quality surface polishing is still an extremely challenging task. In particular, the final polishing of complex surfaces without affecting the part geometry often remains a problem. A newly developed technology allows the direct embedding of diamonds into the surfaces of polymer and elastomer polishing tissues and sponges without the use of any adhesives. The same technology can be applied for making micro-diamond enhanced brushes with very fine and highly flexible filaments for polishing surfaces of complex geometries as well as customized polishing tools for direct integration in processing machines. This article highlights some of the possibilities as well as limitations of a new generation of flexible, diamond-coated polishing tools.

1. Introduction

The constant request for miniaturization of mechanical components, higher working pressures at injectors and valves, as well as the demand for extended life time, require ever better surface finishings. Typical examples are valve surfaces, gear edges, cutting edges, chip flutes of tools and pressing surfaces of molds. In order to increase the efficiency of series production, it is often desirable to integrate the polishing step directly into the production process. In order to provide solutions to this demand, we have developed a new process for the direct embedding of micro- and submicron diamonds into polymer surfaces, allowing the making of novel technical brushes with highly flexible filaments as well as nanoparticle enhanced elastic precision finishing tools made of foams.

2. State of the art

2.1. Technical brushes

Brushes are particularly suitable for polishing complex shaped surfaces. Due to the flexibility of the filaments the effects of varying contact conditions can be much better compensated for as compared to other finishing methods. After getting into contact with the workpiece surface, the filaments bend toward the plane of rotation of the polishing tool, following the principle of the least resistance and then perform a grazing motion over the workpiece surface [1]. Brush filaments usually consist of plastics materials like PA, polyester PBT and LDPE. At elevated working temperatures of up to 200 °C the more temperature-resistant though more expensive high-performance polymers PPS and PEEK are preferred. Abrasive brushes made from compound materials containing abrasive particles have been used for many years as a highly flexible machining method in industrial production. Typical application areas are surface cleaning, reprocessing components, deburring, edge rounding of cutting edges, surface pre-treatment, surface activation or for polishing complex surfaces made of metals, hard metals and ceramics [2-4].

Figure 1. Typical brush shapes: roller, brush and cup brushes.

Figure 2. Mini brushes. From left: brush, pot- and pipe brush.

Abrasive plastic brush filaments are usually made by extrusion. The plastic granules fed to the extruder usually consist of thermoplastics like PET, PA or the more temperature-resistant but considerably more expensive PPS and PEEK. Hard and abrasive materials like Al_2O_3, SiC, or diamonds are homogeneously co-extruded and embedded in the polymer matrix at a typical volume ratio of 20 to 30 %. Higher volume ratios will result in too brittle filaments. Figures 3 and 4 show a scanning electron micrograph of a typical filled filament. It can be seen, that a substantial portion of the abrasive particles is completely enclosed by the polymer matrix.

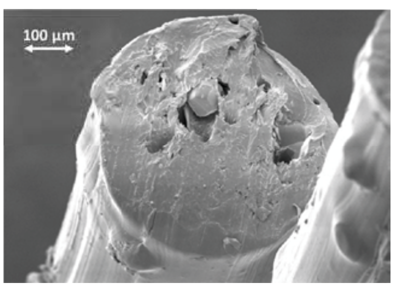

Figure 3. SEM image of a particle-filled brush filament. Head view.

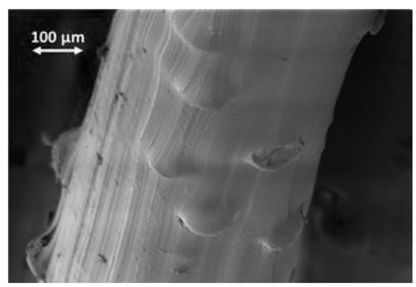

Figure 4. SEM image of a particle-filled brush filament. Side view.

Filled filaments are more brittle and stiffer than unfilled filaments. In most cases, brushes are made up of tufts of filaments rather than single filaments. For tuft stiffness [5]:

- The stiffness (resistance to bending) of a tuft of round filament is proportional to the 2nd power of the filament diameter.
- The stiffness of a tuft of round filament is inversely proportional to the 3rd power of the length of that tuft.

Therefore, the advantage of easy contour following of highly flexible filaments is consequently limited when using brushes with filled filaments. Furthermore, wear of the brush causes the change of tuft length and, as a consequence, dramatic change of the brush stiffness. Latter makes automated application of brushes made of filled filaments for high end finishing operations nearly impossible. A possible solution would be to make filled bristles of smaller diameter filaments. However, the practical feasibility of brushes made of very small diameter filled filaments is limited by their commercial availability. The minimum diameter is 0.3 mm. Another disadvantage of filled filaments is that the abrasive particles must get laid open from the polymer matrix by the polishing process itself, requiring a high relative speed of 20 – 30 m/s between brush and workpiece. The stiffness of a brush increases with rotation speed. Although, the high cutting speeds are needed to partially melt the surface of the filaments. This ensures a continuous release of the abrasive particles. Polishing of the surface and grinding of the tool (brush filaments) take place simultaneously. The resulting thin layer of melted polymer in the contact zone reduces the efficiency of the abrasive particles, especially for particle sizes below 10 microns. The melting of the matrix can also lead to a contamination of the workpiece surface with polymer material, which must be cleaned off subsequently.

2.2. Foams

For manual and mechanical polishing of larger surfaces mainly soft and highly elastic foams made of ethylene vinyl acetate (EVA) or polyethylene (PE) are used as the polishing tool substrate because their high elasticity and porosity provide for an excellent distribution of the contact pressure. More expensive polishing pads are made of PU (polyurethane) and are preferably used in the optical industry for fine polishing of optical glasses [6].

If foams are to be outfitted with one or more abrasive surfaces it can be done by coating the foam with phenolic or epoxy resins and subsequently electrostatically depositing abrasive particles onto the surface before the resins are cured. Another method is to just paste a previously hard particle coated fleece or other type of PA fabric to the foam surface. The most critical part of this setup is the interface between the foam and the abrasive layer since in general it tends to reduce the flexibility of the tool which in turn reduces its contour following capability.

As it is the case with abrasive brushes made of filled filaments, also in coated foams the abrasive particles are wrapped-in or encapsulated by the adhesives and become exposed to the open only by friction during the polishing process. Compared to brushes, the variety of commercially available foam polishing tools is relatively small and limited mainly to pads and sheet products of different thicknesses causing that elastic foams coated with hard materials are currently being used less frequently in industrial applications.

3. Adhesive-free diamond coated brushes and elastic foams

In this program we have developed a new and patented method for the direct, adhesive and binder-free implantation of diamonds onto the surface of polishing tools. The main focus of the development was to combine the advantages of flexible and elastic tools with the higher removal rate of tools with bonded / guided particles. In the here presented new and revolutionary setup micro-diamonds are directly implanted into the surface and the near-surface areas of brush filaments and elastic foams thereby firmly attaching the diamonds to the carrier material surface. The inner composition of the carrier material remains totally unaffected in its mechanical and technological properties since there are no macroscopic or microscopic interface layers necessary in this setup.

3.1. Construction and properties of diamonds implanted brushes

A plastic fiber or a brush filament having diamonds implanted only on the surface has the same high flexibility as an unoccupied filament. Thus, very soft brushes can be designed that can easily follow the changing contours of complex surfaces during automated brushing without damaging them. So far, fibers with a minimum diameter of 15 μm have been successfully surface-implanted with diamonds. Typical fiber materials used are thermoplastics like PET, PA, PPS and PEEK. However, the particle size should not exceed 25% of the filament diameter. With decreasing filament diameter, the particle load becomes even higher compared to filled filaments. For a particle diameter of 25 % of the filament diameter the particle load can reach nearly 55 vol%. Additionally, the diamonds are free standing and ready for immediate use.

Figure 5 illustrates the good surface coverage and excellent adhesion of diamonds deposited using the newly developed and patented implantation method. It can also be seen that the diamonds are mostly exposed to the open and that the smoothly rounded filament tips show a good uniformity. The exposed abrasive particles allow for dry polishing of surfaces with the brushes moving at relatively low relative speeds while at the same time ensuring high abrasion rates. The relative speed is in a very beneficial range of only 0.2 to 5 m/s as compared to 20 to 30 m/s when using brushes with filled filaments. At these low speeds only an extremely low level of unwanted friction abrasion and wear takes place, rendering any subsequent cleaning work virtually unnecessary.

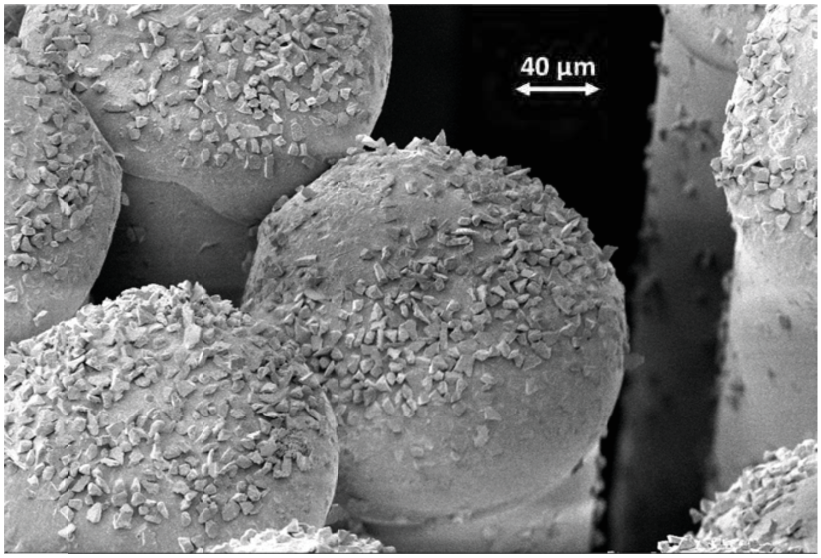

Figure 5. PA fiber surfaces implanted with monocrystalline diamonds.

Depending on the filament length and diameter, polishing work can be carried out even in deep and recessed areas down to the centimeter range on surfaces with complex shapes. Typical penetration depths are in the range of 0.3 to 5 mm. A further advantage of the high flexibility of the filaments is that smaller fluctuations in the tool positioning do not have a decisive influence on the quality of the surface treatment. Positioning errors in the millimeter range merely lead to a slight bending of the filaments or the filaments just yield to the incoming object (for surfaces with fine topological structures in the millimeter range). Only in the effective range (0.2 – 3 mm penetration depth) does the relative position of the filaments towards the surface enable active engagement of the diamonds. This property allows even the processing of the interior of comparatively deep and narrow grooves and also undercuts without affecting the geometry of the component surface.

3.2. Structure and properties of diamond implanted foams

So far, two different foam types have been investigated for their suitability for adhesive-free occupation with diamonds. On the one hand mixed-cell polyurethane (PUR) foam elastomers and on the other hand open-cell, medium-hard foam made of low-density polyethylene (PE-LD), which is often used for final polishing of paint coated surfaces. The PE-LD foam shows a net-like structure while the PU foams are more similar to a bubble structure (see figure 6). Tools made of PUR foams could be coated with diamonds with grain sizes starting from 0.1 µm up to 200 µm, while the fine mesh structure of the PE-LD foam prevented the deposition of diamonds larger than 60 µm.

The open-cell structure of the PE-LD foam was found to be beneficial for the dry polishing of softer materials like paints, polycarbonate, Al, Cu, stainless steel as well as Titanium and its alloys. Due to the smaller contact area and because of the lower coefficient of friction (µ against steel is between 0.25 up to 0.3) compared to the polyurethane foam (µ against steel = 0.5), the surface undergoing polishing is heating up to a much lesser extent. Also, this structure favors the uptake of a liquid cooling medium. The only disadvantage is the early softening point of about 80 °C. However, surface temperature measurements during dry polishing of polymer-based gel coats on GFK-structures never exceeded temperatures of 50 °C (polishing was done at RT).

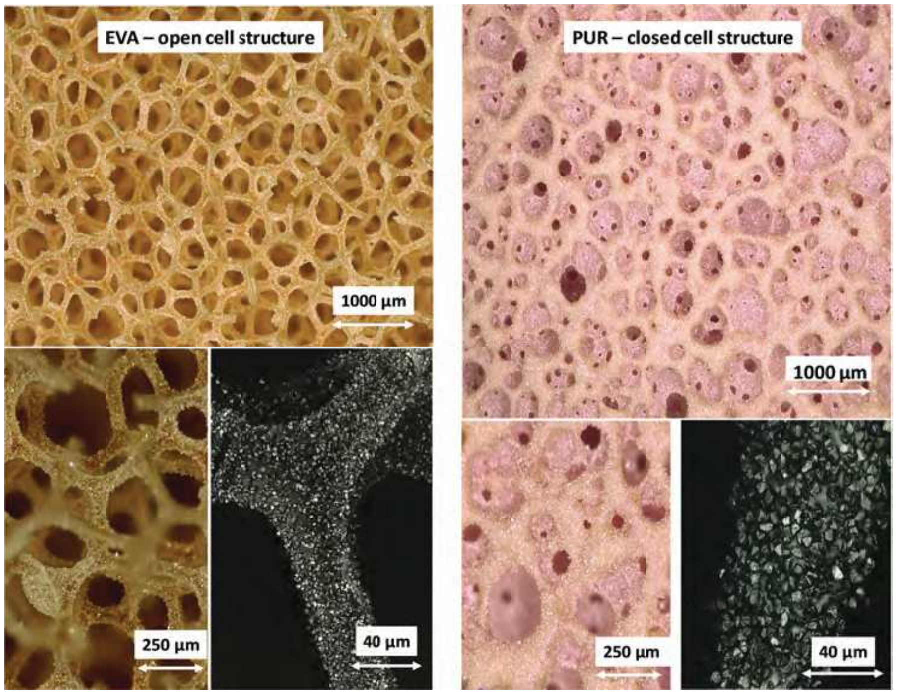

Figure 6. Surface of monocrystalline diamond implanted foams; grain size 6 - 12 µm; left hand – open cell structured PE-LD foam; right hand – closed cell structured elastomer PUR foam.

The mixed cell structure and the rubber like behavior of the tested PUR foams showed a higher dimensional stability and abrasion resistance than the PE-LD foams. When finishing hard materials (hardened steels, hard metals and ceramics) and for the finest finishing quality, the better results were obtained with PUR foams and diamond grain sizes between 3 – 30 µm. However, experimental work is still in progress. So far, we have confirmed that both foam types can be used for dry as well as wet polishing, however quantitative comparative investigations are still in progress.

First attempts to produce defined geometric polishing shapes according to FEPA standard "Shapes and dimensions for superabrasive wheels" were carried out [7]. In particular, the elastomer PUR foam allowed the economic production of very small tools with a minimum diameter down to 1 mm, made from large samples of plate and block material. Using shaped samples cut out of large plates increases the reproducibility and homogeneity of the foam properties, which is a crucial requirement for automated industrial applications of polishing tools.

4. Applications

The following paragraph gives some application examples for the use of highly flexible and elastic polishing tools manufactured following the above described methods. Figure 7 shows the final polishing result of a watch case made of TiC-Ni carbide. The flexible filaments provide for a non-destructive yet effective polishing of the complex shaped surface. Table 1 shows the roughness parameters R_a and R_z of a TiC-Ni Cermet watch case before and after a two-minute brushing treatment with our technology in comparison to an eight hours conventional frictional grinding. The filament length is 25 mm with a filament diameter of 250 µm and a brush diameter (roll brush) of 120 mm. Synthetic, mono-crystalline diamonds with a grain size of 3 – 6 µm were implanted on the surface of the PA 6.6 filaments. The relative brushing speed was 1.3 m/s. The penetration depth was in the range of several millimeters. Results with a finishing surface quality comparable to a two minutes brushing using our technology were achieved by conventional frictional grinding only after a processing time of 8 hours in an aqueous SiC suspension (1 – 3 µm) with cylindrical ceramic grinding wheels.

Figure 7. Soft brush finishing of a watch case (grey subject left hand); rotating brush (right hand).

Table 1. Comparison of surface roughness of a TiC-Ni cermet watch case, finished by different techniques.

	R_z in µm	R_a in µm
Initial state	0.65	0.09
Brushed using new technology, processing time 2 min	0.33	0.04
Conventional friction grinding, processing time 8 h	0.45	0.04

4.1. Removal of droplets

PVD hard coatings, in particular applied by ARC-PVD or magnetron sputtering, often have process related microscopic irregularities on the component surface, so-called droplets. To ensure the full functionality of the coating, these droplets must be removed. In case of hard coatings (e.g. TiC, TiN, DLC) this might be a challenging task. Figure 8 shows the AFM surface profile of a DLC hard coating before and after brushing using our technology. Brush type: roller brush, OD 220 mm, B 80 mm, filament length 250 µm, filament diameter 200 µm, filament type PA 6.6, diamond grain size 8 – 12 µm. The size of the surface area to be treated was 5 x 20 mm^2 with a positive crown radius of about 100 mm. The decisive factor in this application is that the geometry of the component and the functional thickness of the coating have to remain unchanged. Our brushing process solved the problem. The soft filaments guarantee for protecting the surface from any damaging while the bonded diamond grain has enough energy to remove even hard microscopic droplets.

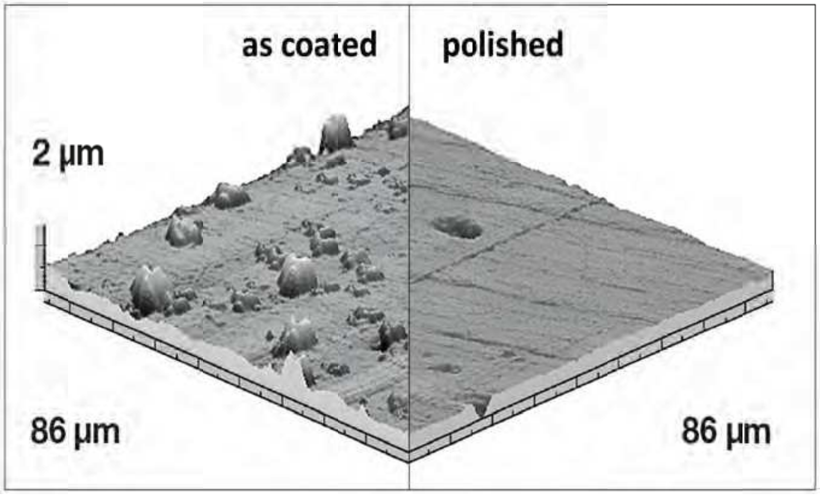

Figure 8. AFM measurement of a DLC coating before and after brushing. Brush advance 2 mm; Relative speed 2.3 m/s; Processing time 20 s.

The problem of increasing the load bearing of smaller components of complex geometry is a constantly recurring challenge. Figure 9 shows the photograph of a PUR foam tool with a head diameter of 2 mm. This polishing pen is intended for integration into a machining center. The Pt value of 100Cr6 valve seats could be reduced from 0.65 µm to 0.16 µm within 5 seconds while the geometry of the valve seat remained unchanged within the required tolerance range. The same tool coated with 10 µm diameter diamonds was used to decrease the surface roughness of a finely structured injection mold made of tool steel. The original surface roughness of 150 nm R_a was reduced to 5 nm R_a.

Figure 9. Polishing pen with head made of diamond-coated PUR foam; monocrystalline diamonds, grain size 8-12 µm.

4.2. Cutting edge rounding

Other common problem areas are defined edge rounding, polishing of the chip flute, as well as the reduction of the chipping of tools. All these parameters, when optimized through proper polishing, can contribute to a significant increase in lifetime of the workpiece. The flexible brush filaments of the brush technology presented here in combination with the further advantage of the freestanding diamonds allows for damage free high processing speeds while simultaneously enabling machining of complex workpiece geometries like for instance HM miniature tools. For example, a radius change of 1 µm/s could be achieved on HM cutting edges with a radius of 5 µm. The roller brushes used were of the same construction as described in section 4.1.

Figure 10 illustrates the possibilities for edge processing of an HSS tool. Also for this task a roller brush was used as described in section 4.1. The positioning was done in the millimeter range in order to ensure optimum polishing of the flutes.

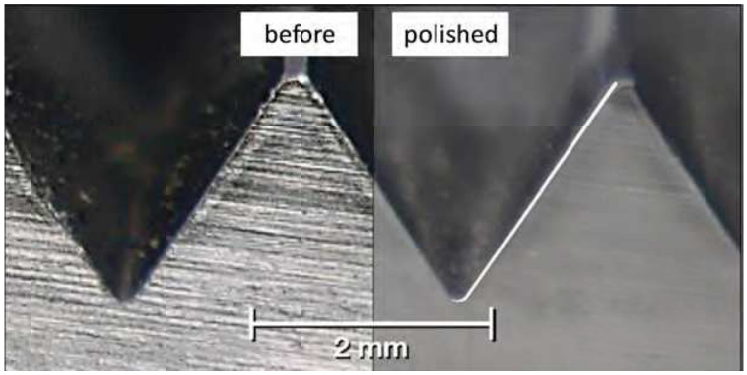

Figure 10. Edges of an HSS tool before and after brushing.

4.3. Polishing gel coats

While the previous examples were predominantly hard surface treatments, the next examples also demonstrate the benefit of using these new tools for the treatment of soft materials.

For instance, polishing weathered gel coats on GFRP surfaces with diamond-implanted highly elastic foams enabled an increase in processing speed by a factor of 2 to 4, compared to the usual processing with uncoated polishing sponges in combination with suspensions. The pads were made both of soft polyurethane foam as well as PE-LD foam, implanted with diamond grain sizes of 0.5 µm, 1 – 3 µm and 8 – 12 µm. Even heavy matting and gray haze could be removed in a single processing step. A comparable surface quality can be achieved using the conventional procedure only with at least two sequential operations, i.e. pre-grinding (use of abrasive suspensions with P1500 and P2000 grits) and polishing (use of abrasive suspensions with P3000). We demonstrated that for achieving the same surface quality using our new technology a sponge covered with diamonds in the grain size range 8-12 µm is sufficient. The abrasion rate could be influenced by the applied pressure. Relatively low speeds in the range of 300-500 rpm were recommended for polishing pads with a diameter of 150 mm. Although a subsequent use of foam pads with even finer grains is no longer necessary it can lead to an even higher gloss. In general, the polishing was carried out dry. Paint abrasion and debris trapped in the sponge pores could be easily removed from the sponge in a water bath without any detergent necessary. A decrease in the abrasion rate over the duration of the test series was not observed. It should be noted that until now surfaces up to a size of 50 m^2 have been polished successfully with a single pad. Only extremely weathered surfaces or paint surfaces with deep scratches required an additional polishing step. A PUR sponge proved to be particularly suitable with diamonds of grain size D63. Another advantage of dry polishing is that the surface stays free of liquid chemicals and other contaminants. Immediately after the polishing the surface is highly activated, so that subsequently applied protective layers show a much better surface bonding. Previous tests reveal an up to a factor 3 longer lifetime of the protective coatings (sealings). Also, the surface treatment can be easily done in direct sunlight and both at elevated temperatures as well as below freezing. The polishing can be done even in saltwater conditions due to the good dust trapping properties of the pads in combination with the dry processing (no liquid chemicals).

5. Conclusions

Direct and adhesive-free embedding of diamonds into the surface of soft, flexible and highly elastic polishing tools such as brushes and moldings made of foams opens up new ways for the efficient finishing of complex and finely structured surfaces. Current applications are only the first steps into a very wide range of possible future applications.

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