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Development and Analysis of Microstructures for the Transplantation of Thermally Sprayed Coatings

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Abstract

Thermally sprayed coatings and tribological surfaces are a point of interest in many industrial sectors. They are used for better wear resistance of lightweight materials or for oil retention on surfaces. Lightweight materials are often used in the automotive industry as a weight-saving solution in the production of engine blocks. For this, it is necessary to coat the cylinder liners to ensure wear resistance. In most cases, the coating is sprayed directly onto the surface. Previous research has shown that it is possible to transfer these coatings inversely onto other surfaces [1]. This was achieved with plasma sprayed coatings which were transplanted onto pressure-casted surfaces. These transplanted surfaces exhibited better adhesive strength, smoother surfaces, and lower form deviation compared to directly coated surfaces. Additionally, it was shown that even microstructures of a surface coated by plasma spraying can be transferred to pressure-casted surfaces. This paper presents the development and micromilling of different microstructures for transferring thermally sprayed coatings onto pressure-casted surfaces. In the development process, microstructures with different shapes and aspect ratios as well as thin tribological surfaces are designed in order to evaluate the advantages and limitations of the transplantation process. In subsequent experiments, the micromilling process and a simulation of the coating transplantation are presented and analyzed.

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1. Introduction

The interest in surfaces with special behaviors or tribological characteristics is ever increasing. In many industrial sectors surfaces with task-specific properties are needed. The automotive industry, for example, uses aluminum engine blocks for weight reduction purposes. To increase the wear resistance of the cylinder liners, a thermal spraying process like Atmospheric Plasma Spraying (APS) or Electric Arc Wire (EAW) is used in certain applications. It is possible to apply different kinds of materials to enhance specific surface characteristics, such as the coefficient of friction. The bores then need to be post-machined in order to fulfill certain geometrical and roughness characteristics. Another example is the deep drawing process, in which it is of prime importance to have a highly wear-resistant drawing radius with a smooth surface. To enhance the material flow while drawing the blank, it is possible to have different kinds of surfaces on the inner radius of the drawing die. One potential method for creating these features is for the drawing die to be thermally sprayed with a wear resistant coating prior to grinding or polishing it to its final finish [2]. These processes reach their technical limits as they are used in increasingly complex geometric

configurations. An obvious technical limitation of the process is that it can only be used if the drawing diameter is large enough to accommodate the thermal spray torch. In addition, the adhesive strength of the layer is not as high as needed for some applications [3]. The need to rework the surfaces to obtain a tribological effect as well as sufficient roundness and shape tolerances presents a further disadvantage. In the past, methods have been developed to transplant thermally sprayed coatings from specially treated pressure casting molds onto components [4]. An expected advantage of this is, that the coating has a higher adhesive strength than one which has been directly sprayed onto the component. Furthermore, it is possible to provide surfaces with a tribological negative microstructure, thus reducing or even eliminating the necessity for reworking. In this context, various microstructures are developed for transplanting thermally sprayed coatings with tribological surface characteristics specific to their application. An analysis into the extent, that the manufacturing of these microstructures is possible, is provided within the context of micromilling processes. It is important to clearly establish the limitations of the transplantation process and examine whether it is possible to transplant filigree microstructures. Finally, it is shown that the resulting transplanted surfaces obtain all necessary requirements.

2. Development of microstructures

To demonstrate the limitations of the transplantation process, it is necessary to investigate different kinds of geometric aspects and corner shapes. Furthermore, it is important to determine where the maximum feasible structure ratio is settled by varying heights or depths and at which ratios the transplanting process is no longer possible while taking practical manufacturing aspects into account. To this end, eighteen microstructures, a negative honing structure and two different kinds of negative pit structures have been created (Figure 1). The eighteen microstructures comprise an array of grooves and small ridges which are made up of different geometric elements such as circles, spirals and linear elements. These microstructures are then tested with planar, round, and tapered groove bases. One of the small ridges is beveled at an angle of twenty degrees to ascertain whether it has a positive influence on the transplantation process. All eighteen structures have different aspect ratios and a maximum height or depth in the range of 100-400 µm, with a surface size about 25 mm^2. The negative honing structure is based on the surface produced by the original honing process and inverted for the transplantation process. The negative honing grooves have the form of tapered ridges with a height of 10 µm, a honing-angle of 45°, and a center distance of 190 µm. The negative pit structures, according to a direct structuring process which uses a rotating piezo-driven tool to create pit structures on rotatory workpieces [5]. They have a length of 2.4 mm and a width of 200 µm with two different heights of 6 µm and 30 µm. These various height values are used to determine whether the oil retention volume can be regulated with structured transplanted surfaces. The last two structures are developed to show that even filigree microstructures measuring structure heights of roughly 10 µm can be transplanted.
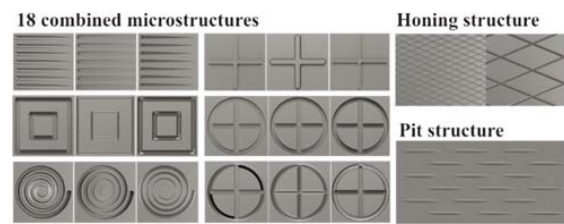

Figure 1: Developed microstructures

3. Machining of structures and analysis

A micromilling process is used to produce the microstructures. When structuring oversized workpieces regarding to micromilling machines it is necessary to use processes which are capable of handling large dimensions. The machining of these specific microstructures is thus performed on a DMG HSC 75 machining center with linearly driven axes and compared to those machined on a DMG 50 EVO machining center with regular spindle drives. For the following simulation of the transplantation process, all microstructures must be placed on tensile specimens. These tensile specimens are made out of X37CrMoV5-1 and hardened to 48 HRC prior to structuring. Machining is then done with three different types of micro-grained tools, non-coated, with diameters ranging from 0.2 mm to 0.4 mm. For small tools, the cutting speed is limited by the maximum spindle speed of the machine (Table1). Depending on the structure's geometry, a ball mill or end mill was used.

Table 1: Tools and cutting parameters

Tool	Ball Mill	Ball Mill	End Mill
Diameter	0.2 mm	0.4 mm	0.4 mm
Machine RPM	28000 1/min	28000 1/min	28000 1/min
Cutting speed	17 m/min	35 m/min	35 m/min
Tooth feed	0.004 mm	0.004 mm	0.004 mm
Max. cutting depth	0.166 mm	0.02 mm	0.02 mm
Number of flutes	2	2	2

In most cases the machining is done by 3-axis operations. Only for the tapered groove bases a 5-axis hobbing process with an end mill cutter is used. Since air cooling is sufficient, all cutting processes are performed without lubricant cooling.

During the micromilling process, it was possible to maintain tight tolerances. Despite the substantial kinematics of the machining center it was possible to create structures in a tolerance about ±2 µm. Particularly for the negative honing and pit structures, the machined surfaces demonstrated accurate form and shape tolerances. The direct comparison of the target measurements and geometry with the machined workpiece yielded a good correlation. Figure 2 shows a cross section through the middle of a pit from the negative pit structure with a maximum height of 30 µm, measured with a confocal light microscope. The measurement shows that the milled structure
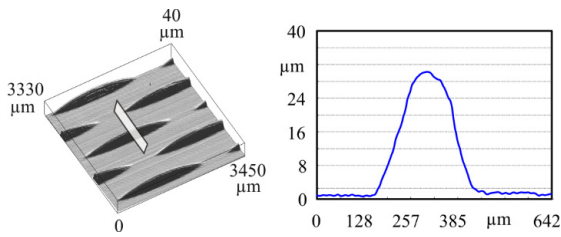
Figure 2: Sectioning through a pit of the negative pit structure with a maximum pit height of 30µm measured by a confocal microscope

conforms tightly to the CAD geometry and has only a few deviations on the bottom of the pits.

In those cases, where the tool diameter was relatively high in comparison to the small structure geometry, an expected form deviation was observed on the bottom of the negative honing and pit structures. The only possibility to reduce the deformation in this case is to use a smaller tool, but due to constraints determined by tool breakage it was not possible to use tools with diameters less than 0.2 mm on the machining center.

Defective surfaces or high shape deviations only occurred on the bottom of some structures. These resulted in part due to tool changes which were performed when necessary because of design constraints or tool wear. In those cases, where a tool change was performed, it was nearly impossible to perfectly match the heights, resulting in inadvertent burr formations on the bottom of some structures. The machining center was not equipped with a magnifying camera system so it was not possible to use a scratching test. Instead of using this test to minimize height differences resulting from tool changes while micromilling, tool changes should be avoided to reduce defective surfaces. When working with hardened materials, the end mill cutter demonstrates high wear in its corner areas which leads to defective cutting edges. Depending on the feed direction of the tool, different defects in the structures can arise. An example of these defects is shown in SEM pictures in Figure 3. On the base of the groove, the up milling and down milling sides show defective surfaces in the corner area. On the up milling side, the material looks shattered and rough while on the down milling side the material looks smeared and smudged.
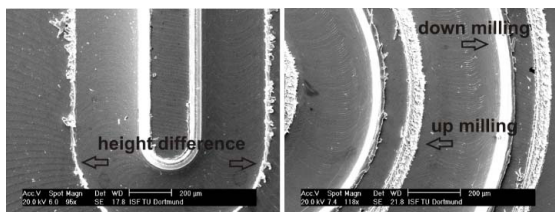

Figure 3: SEM picture of appeared structure defects

Because the worn cutting edges of the end mill cause the material to be deformed and squeezed, it is not possible to guarantee good cutting operations. This leads to the typical ploughing effect which often occurs when the ratio of chip thickness to the rounding of the cutting edges attains a high ratio [6]. To gauge how strong the influence of the machining center on the process could be, a direct comparison of different machining centers showed that the structure quality is dependent on the type of machining center used. The results of manufacturing the smallest structures on the DMG 50 EVO machining center were not of the same quality as those produced by the DMG HSC 75. The machined negative honing structure is not very smooth and shows a nearly shattered surface with ragged ridges. Furthermore, the height of the structure geometry of the ragged ridges fluctuates by about 5 µm (Figure 4). This is not only because the former machining center is an older series; the primary reason for this could be the use of different types of axle drives. Direct drive motors have less moving parts and therefore less mechanical clearance and deformation. The reversal range is lower and it is thus easier for the internal machine regulation to compensate for deviations in position [7].
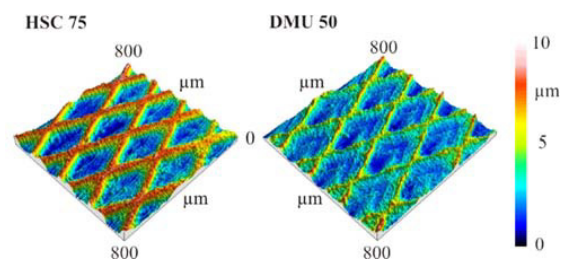

Figure 4: Comparison between different machining centers with a machined honing structure

4. Simulation of the transplantation process

In a normal transplantation process for thermally sprayed coatings, the specimens are thermally sprayed, pressure cast, and subsequently separated by a tensile test machine. For a simulation of these, the pressure cast step is exchanged to a gluing process. Therefore the simulated transplantation process consists of the structured specimens being thermally sprayed by plasma spraying and glued on non-structured specimens. Afterwards, separation is achieved with a tensile test machine, as it would be in the normal, non-simulated process Figure 5.
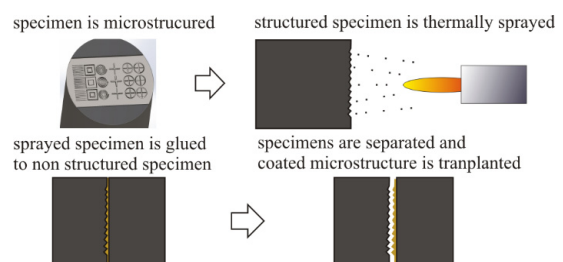

Figure 5: Schematic illustration of the simulation for the transplantation process

In the experiments two different kinds of coatings have been used. The first is a NiCr 80/20 coating with a low powder grain size which has excellent adhesive properties and is often used for establishing adhesion between multilayer coatings. It also has good corrosion and oxidation properties. The second is a CuAL 10 coating with a medium-sized powder grain which has good resistance against metallic slide friction and a high resistance against displacement. The thickness of the sprayed powder is about 250 µm with a spraying angle of 90 degrees. Because of the small size of the specimens, other spraying angles were not tested. The buildup of the coats would not be of the same quality because the spraying nozzle is large relative to the specimen. After the spraying process the second specimen was glued with a UHU Plus Endfest 300 glue (UHU GmbH & Co KG) on the top of the sprayed surfaces. After the common drying time the specimens were separated by a tension machine according to DIN EN 582.

5. Results of the transplantation process

5.1   Geometrical limitations

In order to combine different geometrical elements for transplanting structures it is necessary to distinguish between different aspects. One of the aspects is the geometry itself. Tests of round and straight structural elements showed that better results were attained by the use of the former. Particularly in areas with sharp corners, a higher incidence of defects or even a complete failure of the transplantation could be observed. One main cause for this is that the coating in the spraying process could not always penetrate into the corners of the structure. Even when a complete corner penetration was achieved, the separation did not work consistently because clamping of the coatings in these areas was too high. Another cause can be attributed to the geometry of the groove base. These showed nearly the same results as for the geometry of the structure itself. In the experiments where three different kinds of groove bases were tested (round, tapered, flat), the round and the tapered bases showed the best results. Depending on their aspect ratio it was possible to transplant nearly all structures with these kinds of bases. Figure 6 shows a combination of different geometrical elements and groove bases. It is noticeable that the transplantation works for both the round structure geometry and the round groove base. The coating of the ring is nearly fully transplanted to the glued specimens. Only of the straight and sharp geometries the coating could not be transplanted completely. A particular source of problems, however, was the combination of structural elements with different groove bases. As shown in Figure 6, it was not possible to transplant the structure without defects in the regions containing intersections of differing groove bases. To ensure an accurate transplantation, it is important to reduce this kind of intersection between groove bases that are easy to transplant with those that are more problematic.

The difference between ridges and grooves must also be considered. The use of grooves does not deliver the same result as using ridges. For example, the transplantation of ridges succeeded more often in the experiments performed and with higher aspect ratios than with grooves.
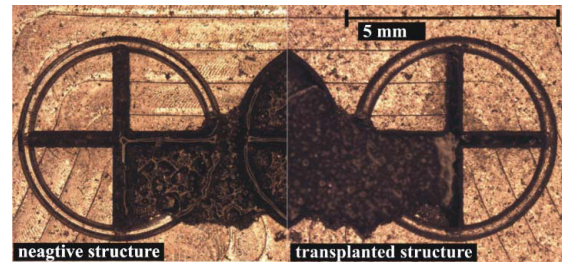

Figure 6: Comparison between negative structure and transplanted coating

One very important limitation for developing micro-structures for coating transplantation is the aspect ratio of the geometry. In the experiments a width of 400 µm is combined with different heights (ridges) or depths (grooves) to test different aspect ratios. The results show that it is possible to transplant coatings with a maximum height or depth around 300 µm with an aspect ratio up to 0.75. A good example of this is shown in Figure 7 were a cross section shows the maximum attainable transplantation height. The figure shows that after reaching a structure depth of $h_0 = 283$ µm the transplantation of the coating was no longer reliable. These results were verified for various geometries and groove bases as well as for ridges and grooves. In some cases it was even possible to transplant aspect ratios up to 2, but it is nevertheless recommended to use structures with a lower aspect ratio in order to ensure a defect-free transplantation.
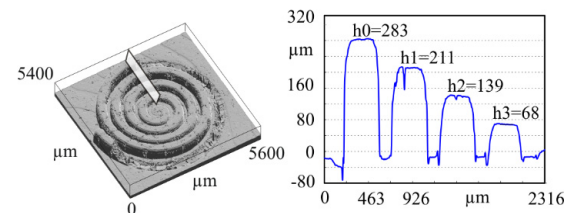

Figure 7: Transplanted spiral structure with a sectional view through the maximum reachable transplantation height.

5.2   Differences between coatings

In the experiments it was shown that it is possible to transplant microstructures with different forms, groove bases, and aspect ratios, with different coatings yielding different transplantation results. Figure 8 shows a direct comparison of two transplanted spiral microstructures by using different types of coatings. As is seen in the figure, the structures were not completely transplanted when using planar groove bases and an aspect ratio of 1. It was shown that the CuAL 10 coating, which has a middle size powder grain, is more prone to defects on the transplanted microstructures. For both planar groove bases and straight and sharp geometries, defective or non-transplanted areas could be found, especially in the corner areas of the flat groove bases (negative seen). Possible causes for
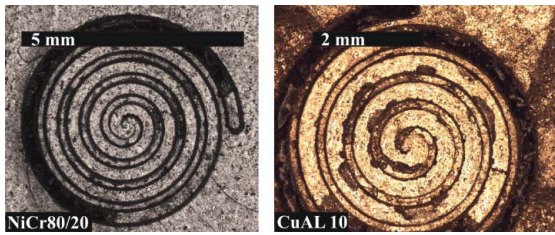
Figure 8: Comparison between NiCr 80/20 and CuAL 10 coating

these defects could be the grain size or the lower adhesion of the coating. In addition, the transplantation showed that the complete breakaway of the structure occurs at a lower ratio than for the NiCr 80/20 coating. The NiCr 80/20 coating material possesses a much better surface quality and can be built up to much higher aspect ratios. Because of the small grain size of the NiCr 80/20 and its superior adhesive qualities, the whole structure is smoother and less porous.

From these observations it is clear that the use of different coatings is linked to the design of the microstructure. As such, care should be taken that the microstructure used fulfills all necessary criteria for a successful transplantation.

5.3 Filigree microstructures

The transplanted results of the filigree negative pit and honing structures displayed good shape and forming characteristics. In this case it was possible to transplant all variations of the negative pit and honing structures.

5.3.1 Pit structure

With the development of the negative pit structure it should be shown whether it is possible to design microstructures that can affect the characteristics of surfaces. Especially in the case of creating surfaces with different oil retention characteristics, this is tested with two different types of negative pit structures. The variations result from the different negative pit heights used (6µm and 30µm) are intended to show that the transplanted coating can provide the same oil retention as the milled structure. Figure 9 shows a comparison between a milled negative pit structure and the transplanted coating (NiCr 80/20). The direct comparison of the milled structure and transplanted coating shows relatively small form deviation. Failures only appear in the smoothness of the transplanted structure which depends on the type of coating. By using a
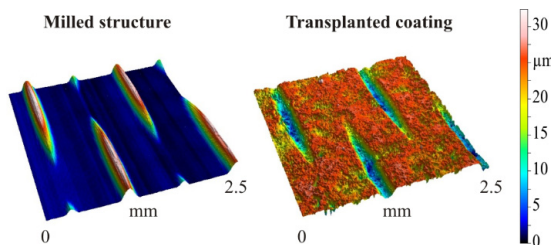
CuAL 10 coating, for example, the open cell character of the coating is such that the full shape of the 6 µm is not clearly discernible. In contrast to this is the behavior of the NiCr 80/20 coating which has better properties relating to the open cell character. As seen in Figure 9, the transplanted surface looks rougher than that of the milled structure; however, for a sprayed surface without any rework, the quality has good characteristics compared to a directly sprayed surface.

Upon closer inspection of the bearing area curves in Figure 10 and Figure 11 it can be seen that it is possible to create surfaces with different characteristics. In Figure 10, the transplanted surface has a relatively high material ratio as well as a planar surface. Additionally, an oil retention of $v_0 = 0.047\ mm^3/cm^2$ was reached, which is close to the calculated value of $v_{cal} = 0.0469\ mm^3/cm^2$. For good sliding properties, surfaces should show a sigmoidal curve and offer an oil retention capacity larger than $v_{lit} = 0.02\ mm^3/cm^2$ [8]. Both of these attributes are present in the transplanted surface.
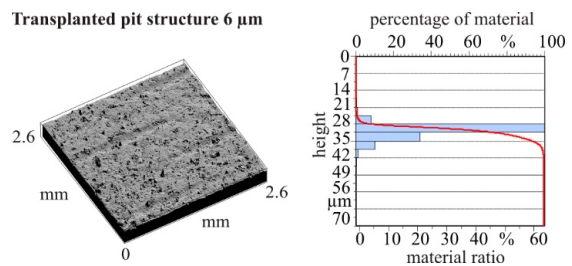

Figure 10: Confocal photo of the transplanted NiCr 80/20 pit structure 6 µm (left) with attendant material ratio curve (right).

The bearing area curve shown in Figure 11 does not reflect a surface as flat as in Figure 10. The reasons for this are twofold. One matter is the use of the CuAL 10 coating, which offers a rougher surface quality than NiCr 80/20. The second is the greater volume of the individual pits developed for this sample. Moreover, the surface also has a sigmoidal bearing area curve, but shows a significantly higher oil retention of $v_0 = 0.167\ mm^3/cm^2$, which is over three times larger than that of the surface with a 6 µm pit depth.

The results attained by using the various negative pit structures developed here show that it is possible to transplant surfaces with tribological characteristics tailored to their intended application.
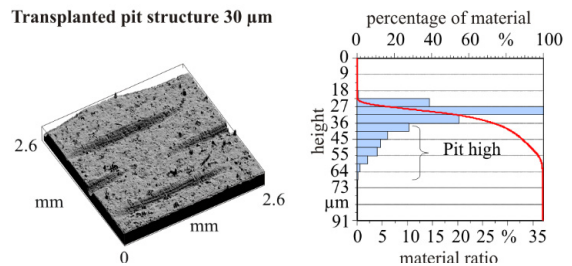

Figure 9: Comparison between milled pit structure (negative, 30µm) and transplanted coating

Figure 11: Confocal photo of the transplanted CuAl 10 pit structure 30 µm (left) with attendant material ratio curve (right).

5.3.2 Honing structure

The negative honing structure should show that it is even possible to transplant microstructures with very small geometrical features. In spite of its small dimensions, the structure itself has good transplantation characteristics, although the process was not equally successful for both coatings. It was not possible to transplant the structure with the CuAL 10 coating. When the open cell character is too large the appearance of these transplanted coatings was not suitable for its intended use. The NiCr 80/20 coating, on the other hand, yielded more favorable results. The transplanted surface is smoother, has less form and shape deviations, and no defective areas. In Figure 12 a comparison between a milled structure and a transplanted coating (NiCr 80/20) is shown. It can be seen that all necessary elements have been transplanted well. The coating fulfills its design requirements. It is obvious that the negative honing structure enabled even small and filigree structures with heights about 10µm to be transplanted. Furthermore it was possible to create a honing structure with specified geometric characteristics without using a honing process.
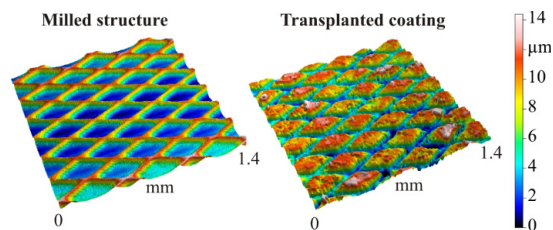

Figure 12: Comparison between milled honing structure (negative) and transplanted coating NiCr 80/20

6. Conclusion and outlook

The experiments performed in the scope of this paper show that the development, manufacturing, and transplantation of microstructures have clearly defined limitations. Beginning with manufacturing, it was shown that the quality of the structure produced depends upon the machining center chosen, as it was not possible to guarantee the same surface quality by using different machining centers. Defective areas and burr formations appeared when tools were too worn or tool changes were performed. Furthermore, it was shown that the filigree structure size compared to the relatively high tool diameter leads to form and shape deviations at the base of the structures. For design purposes, the structures should have round geometrical elements instead of straight ones where possible. In addition to this, the combination of round and straight elements should be avoided to ensure a successful transplantation process. Another consideration is that a maximum depth (grooves) or height (ridges) of 300 µm with an aspect ratio of 0.75 should be maintained. Experiments showed that round and tapered groove bases in the structures lead to less defective areas than flat ones did. Depending on, whether a NiCr 80/20 or a CuAL 10 coating was used, the selection of coating had significant influence on the transplantation

process. Coatings with higher grain sizes and therefore larger open cell characteristics showed more defective or even completely non-transplanted areas. In addition to this the adhesive strength of the coating has a major effect on the probability of success for the transplantation process. The results achieved with negative pit and honing structures show that transplanting even filigree microstructures is possible. By using various pit structures it was possible to generate surfaces with different tribological characteristics, such as oil retention. In the experiments performed, the possibilities and limitations of transplanting microstructures with thermally sprayed coatings were shown. A topic of future research could be to test tribological aspects other than those presented here. Additionally it is to proof, if a subsequent finishing honing process could deliver even smoother surfaces.

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