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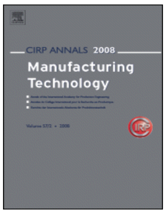

Manufacture of functional surfaces through combined application of tool manufacturing processes and Robot Assisted Polishing

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The tool surface topography is often a key parameter in the tribological performance of modern metal forming tools. A new generation of multifunctional surfaces is achieved by combination of conventional tool manufacturing processes with a novel robot assisted polishing process. This novel surface texturing method allows for a large degree of freedom in specifying surface characteristics and facilitates a high degree of reproducibility between samples surfaces. A series of strip reduction tests, equivalent to a metal forming ironing process, are conducted to benchmark the tribological performance of 15 generated tool surfaces.

Keywords: Tribology, Surface modification, Polishing

1. Introduction

Friction, lubrication and wear related effects are becoming increasingly important in many modern forming processes playing an important role in establishment of forming limits. Examples of research on this subject include the characterisation of workpiece surface topography by open and closed lubricant pockets Geiger et al. [1], the frictional scale effect in metal forming Geiger et al. [2] and the development of a friction model based on this concept explaining the significant increase of friction in microforming Engel [3].

The growing use of high strength materials, smaller components dimensions and advanced, progressive tooling systems in forming processes have further raised the need for well-functioning, tribological systems with a high degree of stability.

Recapturing that a typical tribological system can be simplified into a three-body system, consisting of two sliding surfaces separated by a lubrication layer, it is evident that the surface characteristics of the two solid interacting bodies play a role in the performance of the tribological system. Controlled texturing of workpiece as well as tool surfaces have proven to be valuable in bulk as well as sheet metal forming [4].

Conventionally tool makers rely on a range of surface finishing operations with a high degree of manual interaction. Dies for injection moulding of polymers and metal forming are typically polished to glossy state by skilled craftsmen with help of simple polishing tools, e.g. sticks of wood or plastic provided with diamond paste. These manual finishing operations stands in strong contrast to the remaining of the tool manufacturing, where computer controlled tool fabrication has long been state of the art.

In the following work a novel semi-automatic polishing machine is used to polish a range of simple tools. The application of this Robot Assisted Polishing (RAP) machine offers several advantages over manual polishing. It eliminates the stochastic nature of the manual polishing and enables high flexibility in choice of polishing lay.

2. Methods and materials

2.1. The Robot Assisted Polishing machine

The RAP machine is a prototype machine developed and patented by the company Strecon A/S. The central elements of the machine are a rotational chuck and a pulsation polishing module holding a polishing tool, mounted on a small industrial robot. The machine is capable of operating semi-automatic, which means that only tool and specimen is changed manually, and the required cleaning operation is done by hand. The functional key elements of the RAP machine are shown in Figure 1.

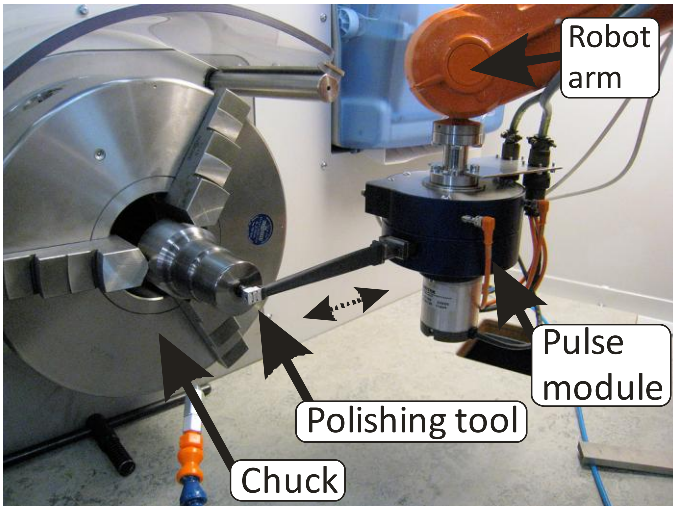

Figure 1. Photograph of the central elements of the RAP polishing machine.

The RAP machine is capable of polishing 2D rotationally symmetric objects through a simple programming interface. The polishing parameters can be changed for each polishing pass, including polishing tool, chuck rotational speed, the oscillating pulse amplitude, the feed rate and the applied polishing force. By a deliberate choice of these parameters and thereby the resulting difference in relative movement between polishing tool and specimen, tailored tool surfaces can be realized with polishing lay in different directions (axial, circumferential or oblique). In the following a series of 15 different tool surface topographies will be produced on a cylindrical tool roll of simple geometry. The performance of each of the polished tools is subsequently assessed using a strip reduction test.

2.2. The Strip Reduction Test

The strip reduction test is a close equivalent to the ironing process known from cold metal forming [5]. The test was chosen based upon its challenging tribological conditions and the open configuration, making it easy to assess the results. Figure 2 show an illustration of the tool geometry and the principle of the strip reduction test.

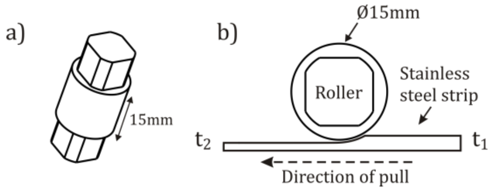

Figure 2. Illustration of the tool roller (a) and the principle of the strip reduction test (b).

The test is suitable for qualification of lubricants as well as tool and work piece material combinations and surface topography influences. Depending on the combinations of parameters, different strip reduction ratios can be chosen. The reduction ratio is given as:

$$R = \frac{t_1 - t_2}{t_1} \tag{1}$$

where, t_1 is the ingoing strip thickness and t_2 is the outgoing strip thickness.

Depending on the choice of parameters, it is possible to provoke breakdown of the lubricant film over the length of the strip, making the strip test sensitive to even minor changes. Further, the geometry of the strip reduction roller allows for up to four repetitions of the test with the same surface topography by turning the roller tool 90° about its own axis. The roller geometry is ground from a bar of hardened and tempered PM high speed steel, (Uddeholm's Vanadis 4E), featuring a hardness of 60-64 HRC. A series of 15 strip reduction tools were manufactured only differing as regards the preceding manufacturing process and the subsequent polishing strategy applied.

2.3. Tool manufacturing and polishing strategy

Each of the 15 tool samples have been placed into four categories according to their pre-machining and polishing, see Table 1. The four categories have been established to investigate the influence of three distinct surface characteristics, supplemented by a set of reference surface scenarios. The tool specimens numbered 1-4 seek to establish the influence of structure and direction of lay in grinding and polishing, tools 5A-5D investigate the influence of polishing in combination with the EDM process and the possibility of creating closed lubrication pockets, tools 6-7 were polished using a rotating polishing tool connected to the RAP machine arm and tools 8-13 were hand-polished, unpolished and best practice examples provided for reference all with lays in the sliding direction. An overview of the tool samples, manufacturing and polishing procedures are shown in Table 1.

Table 1 Categorized list of tool roll samples.

Tool number	Pre-machining	Finishing strategy
1-4 Influence of structure and angle by pulsing	Hard grinding	1. RAP polishing with no pulsation, grinding and polishing lay parallel to sliding direction 2. RAP polishing with slow rotation and high pulsation, grinding lay parallel to and polishing lay dominantly perpendicular to sliding direction 3. Micro-milling of axial surface lay + RAP polishing, grinding and polishing lay perpendicular to sliding direction 4. RAP polishing by combination of rotation and pulsation, grinding lay parallel to sliding direction, polishing lay at an angle of 45° to sliding direction
5A-5D EDM and pores influence	Wire-EDM	5A. RAP, pores from EDM are **clearly** visible 5B. RAP, pores from EDM are visible, but with low Rpk value 5C. RAP, pores from EDM are visible, but with low Rpk value – more polishing 5D. No polishing, surface as manufacturing by wire-EDM
6-7 Rotational polishing module	Hard grinding	6. RAP, Polishing with rotational module on robot arm, grinding and polishing lay in sliding direction 7. RAP, Polishing with rotational module at slight angle, grinding lay in sliding direction, polishing lay at an angle of 5° to sliding direction
8-13 Benchmark and referencing	Hard grinding	8. RAP, polishing according to RAP workshop best practice 9. Manual polishing by craftsman ID: HKS 10. Manual polishing by craftsman ID: LS 11. N/A 12. As 8. but with more polishing in the finishing phase 13. Surface as left by grinding

2.4. Tool Topography Characterization

A metrological surface quantification protocol for assessment of each tool specimen was established. The measurement procedure consisted of a total number of 12 2D roughness measurements, three on each of the four tool facets and one 3D roughness mapping. The 3D roughness measurement was conducted on a 0.2 by 1 mm areas with stylus increments of 1 µm in both directions. The radius of the stylus tip was 2 µm. The approximate location of the 2D and 3D measurement points are shown in Figure 3.

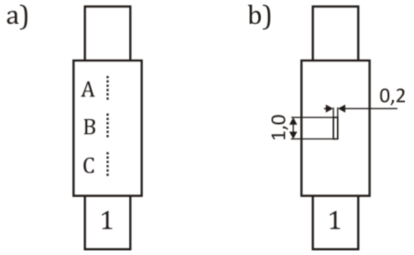

Figure 3. Approximate location of the 2D and 3D roughness measurement points. Measures are in millimetres.

The 12 2D roughness measurements for each tool specimen were filtered and averaged over an evaulation length of 4 mm for each measurement. The average values of Ra, Rz and Rpk are listed in Table 2. It is noted that the values for Ra differs substantially between the 15 tool specimens, an effect that is expected to influence the performance of the strip drawing test.

In the following only results related to tool samples 5B, 7 and 10 will be visualized, as they are considered representative samples of three distinct tool surface textures. However the analysis has been completed for all samples and results are available in Table 2.

A roughness sample of the 2D roughness measurement for the tool numbers 5B, 7 and 10 has been plotted in Figure 4. From these plots it is clear that tool 5B, represents a surface texture with a relative flat plateau and a high spatial frequency of deeper pores from the wire-EDM process as well as a high roughness value. Tool 7 contains a series of valleys with wider spacing and some plateaus in between. Finally the mirror finished tool 10 in Figure 4 has a flat profile with only few deeper scratches.

Due to the nature of the 2D measurements, the orientation and overall structure of the surface topography cannot be evaluated. For this reason the 2D roughness measurements were supplemented by a 3D surface mapping of each tool.

The 3D data have been flattened to remove the influence of tool curvature, but is otherwise not filtered. Figure 5 shows a graphical representation of 3D measurements. For the wire-EDM and polished tool 5B, a surface structure with a high degree of randomness and deep pores can be noted. Tool 7 is characterized by having a table mountain profile with flat, rather smooth plateaus in between regularly distributed scratches appearing under an angle equivalent to that of the rotating tool during polishing.

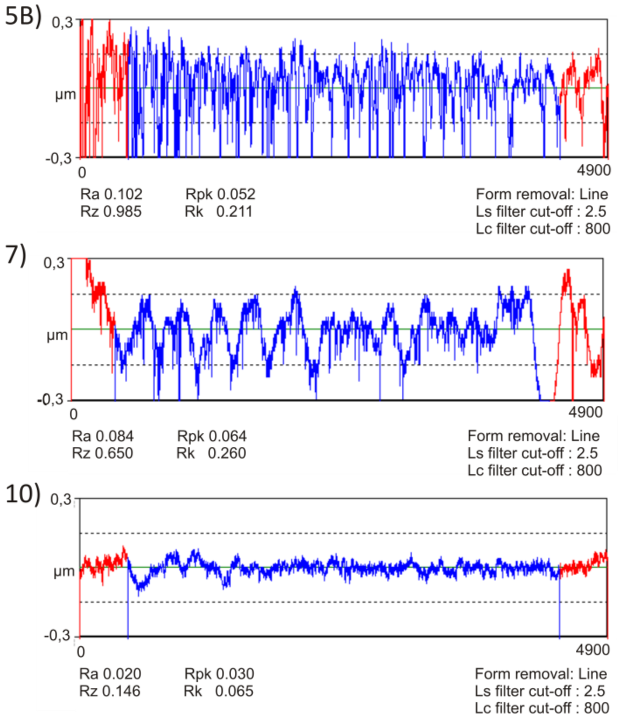

Figure 4. Representative examples of the acquired 2D roughness values for a tool with low Rpk value and some pores left by the EDM process 5B), the tool with a tangential roughness pattern 7) and the hand polished specimen featuring mirror finish 10).

Tool 10 in Fig. 5 shows the 3D roughness map when manual polishing. The surface roughness is low with a very flat profile corresponding to mirror finish. However, an unintended waviness can be noted which can be attributed to the manual polishing operation, where constant polishing force and even distribution of the polishing motion can be difficult to achieve.

Table 2 Summary of tool specimen roughness parameters. The list is ordered according to performance in the strip test, best is first.

Tool number	No. of samples	Nri (>0.5µm)	Nr2 (>1µm)	Polishing procedure	Ra [µm]	Rz [µm]	Rpk [µm]
7	9	21	3	RAP, Polishing with rotational module at slight angle, grinding lay in sliding direction, polishing lay at an angle of 5° to sliding direction	0.07	0.52	0.06
6	9	22	4	RAP, Polishing with rotational module on robot arm, grinding and polishing lay in sliding direction	0.04	0.24	0.04
9	9	26	4	Manual polishing by craftsman ID: HKS	0.01	0.10	0.02
5C	9	30	4	RAP, pores from EDM are visible, but with low Rpk value – more polishing	0.02	0.25	0.02
10	9	29	5	Manual polishing by craftsman ID: LS	0.02	0.13	0.02
12	9	30	7	As 8. but with more polishing in the finishing phase	0.01	0.13	0.02
2	9	31	5	RAP polishing with slow rotation and high pulsation, grinding lay parallel to and polishing lay dominantly perpendicular to sliding direction	0.03	0.34	0.03
8	9	31	13	RAP, polishing according to RAP workshop best practice	0.03	0.38	0.05
5B	9	42	20	RAP, pores from EDM are visible, but with low Rpk value	0.09	0.65	0.02
1	9	48	11	RAP polishing with no pulsation, grinding and polishing lay parallel to sliding direction	0.08	0.63	0.05
4	9	48	23	RAP polishing by combination of rotation and pulsation, grinding lay parallel to sliding direction, polishing lay at an angle of 45° to sliding direction	0.11	1.15	0.07
3	9	73	39	Micro-milling of axial surface lay + RAP polishing, grinding and polishing lay perpendicular to sliding direction	0.03	0.24	0.04
13	8	102	67	Surface as left by grinding	0.10	0.81	0.07
5A	4	125	66	RAP, pores from EDM are clearly visible	0.31	2.15	0.08
5D	Break	N/A	N/A	No polishing, surface as manufacturing by wire-EDM	0.56	3.51	0.39

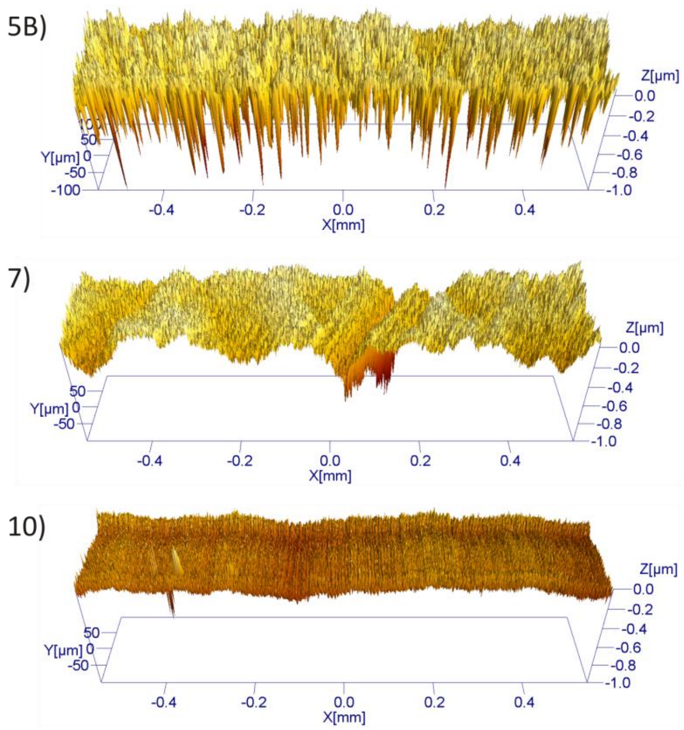

Figure 5. Plots of the acquired 3D roughness data. The curves have been flattened with respect to the curvature of the specimen.

3. Strip Test Results

Each tool roll was tested in the strip reduction test with four repetitions, implying a total of 60 strip tests. Each of the 1×15 mm, AISI 316 stainless steel strips were reduced to 0.7 mm in thickness, equivalent to a reduction ratio of 30%. The commercial lubricant R.rhenus SF 150 A, a mineral oil with Ca, P and S additives and a viscosity 150 cSt at 40°C was applied and testing was carried out with tools at room temperature.

Resulting surface quality of the drawn test strips were evaluated by performing a series of equally spaced 2D roughness measurements along the length of the strip with a distance of 30mm and acquired in a direction perpendicular to the strip draw direction. The resolution of the roughness measurements was chosen to 0.5 µm and a length of 12.5 mm corresponding to 25000 points. The acquired 2D topography data was interpreted using a special strip test protocol. The protocol relies on counting the number of scratches with a depth larger than a certain threshold value. In the present case a two band classification was chosen with threshold values of 0.5 µm (Nri) and 1 µm (Nr2) respectively. This means that a scratch with a depth of 0.7 µm would fall in the first category while a scratch with a depth of 1.1 µm would fall in the latter.

All strip drawing tests showed unchanged condition of the lubricant films and no notable differences of surface topographies could be noted over the length of the strips. This was further confirmed by the roughness measurements of the strip specimens. It is therefore reasonable to apply average values of the roughness measurements over the entire length of the strip as given in the Nri and Nr2 columns of Table 2.

4. Results and discussion

The studied tool surfaces each differ in surface topography as illustrated by the examples in Figure 5. The tool surfaces have been produced by a deliberate choice of 15 distinct sets of pre-machining and polishing combinations. The polishing operation carried out on the novel Robot Assisted Polishing machine, allowed a high degree of control as regards direction of the lay. Strip reduction tests with the different tool rolls were undertaken to characterize the tribological performance of the developed tool surfaces.

The results exhibit good reproducibility when comparing the repeated samples and distinct differences between the different tool textures. As to be expected an overall high degree of correlation between the tool surface roughness value (Ra) and the resulting number of strip scratches was noted, but the specially textured tool surfaces tools 7 and 6 showed the very best performance despite their rather high roughness, which would suggest a performance comparable to the average performance of samples 1 and 5B. This result indicates that an optimal combination of pre-processing and subsequent polishing exists, yielding functional surfaces with superior tribological performance. This finding is in good agreement with results earlier obtained by other researchers conducting similar tests on the influence of topography of tool surface [6] and work piece surface [7].

For the remaining samples it is suggested that the influence of the surface texture, which is supposedly weaker than the overall surface roughness, is concealed by the relatively large overall tool surface roughness deviations. It is suggested that tools with comparable roughness values and different surface texture is studied in future experiments. However, this involves obtaining a high degree of control and predictability of the polishing process.

5. Conclusion

15 different tool surface topographies were created with the help of a novel robot assisted polishing apparatus in combination with conventional tooling processes. The resulting tool surfaces, each structured according to a distinct surface texture and orientation strategy, were quantified using roughness measurement equipment. The tribological performance of the tools was evaluated in a series of repeated strip reduction tests. The results showed good correlation between general tool surface roughness and surface quality of the drawn stainless steel strip. Within the four best performing surface textures, Ra roughness values differed in the range from 0.01-0.07 µm, where the best performing tool surface texture exhibited the highest roughness value of Ra 0.07µm explained by favourable surface texture of the tool. The results indicate the existence of an optimal combination of pre-processing and subsequent polishing strategy for metal forming tools. This optimum will vary with the type of forming process, implying that selection of tool surface texture for optimum performance has to be determined for the forming process in question.

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