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Assessment of Factors in Material Removal by Abrasion using Compliant Contact Wheel with Design of Experiment Method

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Abstract— ***Surface finishing, normally the final step within manufacturing processes, is an important step to improve the aesthetic value or the functional quality of a product. One commonly used method of surface finishing is with the usage of abrasive belts onto a compliant contact wheel. Presently, the aim of surface finishing with the aforementioned method is to be automated. However, theoretical models presently available are not yet mature to meet the stringent requirements of surface finishing. Hence, this study makes use of the full factorial DOE method to determine the effects of six inputs; tool pressing force, spindle speed, feed rate, tool hardness, tool type and surface geometry on the outputs; material removal volume and depth, and surface roughness R_a and R_z. In the case of the average depth of material removal, it was found that only the effects from the type of wheel used is significant, while for the material removal volume, both the effects from the type of wheel and workpiece used are significant. On the other hand, all of the factors are involved in producing interactions with significant effects on both of the outputs. As for the surface roughness, the main factors of feed rate, tool spindle speed and type of wheel are significant to the output of R_a and R_z, while only the factor of hardness is significant with interaction with spindle speed.***

Index Terms— **Design of Experiment, Material Removal, Contact Wheels, Robotic Finishing, Surface Roughness.**

I. INTRODUCTION

Surface finishing is an important step within most production processes, such as the production of fan blades, to achieve the final quality requirements of the end product. For example, one requirement is to increase the lifespan of the product by improving corrosion and wear resistance through surface finishing. Other purposes of surface finishing include meeting the dimensional tolerances of a product, adjusting surface reflectivity and appearance as well as enhancing adhesive ability and chemical resistance [1]. Surface finishing techniques include grinding and polishing, involving material removal from the part surface. Normally, polishing/grinding processes accounts up to around 20-40% of the overall manufacturing costs [2].

One of the conventional methods of surface finishing of geometrically complex parts by grinding and polishing involves the usage of abrasives belts, backed by a surface compliant contact wheel made of a certain hyper elastic material. [3, 4]. Recently, extensive research was done in the automation of surface finishing by grinding and polishing to improve the efficiency of the process which aims to reduce the process time by using a robot arm for the process and implementing an abrasive wear model to predict the wear of the surface [5-7]. The usage of the robot arm allows consistency and speed in running the surface finishing process as well as averting the disadvantages of manual operation from a skilled operator such as human error in judgement and fatigue.

Currently, in the automation of grinding and polishing, the usage of a wear model to predict the material removal from surfaces is greatly limited within the industry as such models are still within its infancy. One of the models commonly used to predict material removal with abrasion using compliant contact wheels is the classical Hertzian Model [8], where such model provides predictive capabilities to certain extent with regards to the pressure distribution values and size within the contact area between the compliant contact wheel and the part surface. Subsequently, the calculated pressure distribution values are used within the Archard Wear Model [9], which uses the pressure values from the Hertzian Model in conjunction with a certain Wear Coefficient to derive a material removal profile [4]. However, the Hertzian Model may not provide accurate values as the model works on certain assumptions [10]:

1. The surfaces in contact are continuous and non-conforming;
2. The strains present are minimal and within the elasticity limit;
3. Surfaces can be assumed to be half-space and can be locally described by orthogonal radii of curvature;
4. The surfaces in contact are frictionless and non-adhesive

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Hence, it may prove difficult to adhere to these conditions in a real world setting and when these conditions do not match that of Hertzian Model assumptions, the actual results can vary from the Hertzian Model prediction though similarities exists [11].

Thus, there is a need for a fundamental understanding of trends developed with changing selected parameter values towards certain outputs in surface finishing with a compliant contact wheel. This paper presents results obtained from abrading work-piece surfaces of 2 types of geometries using different types of contact wheels (flat or serrated types) using the full factorial 2k Design of Experiments (DOE) method, including adjusting selected process parameter (factors) levels such as tool pressing force, hardness, spindle speed and feed rate. The purpose of the aforementioned results is to determine the trends on the selected outputs of material removal volume, depth and surface roughness, and to "screen" the selected factors to determine the useful ones for each selected output, which may aid in future studies involving material removal by abrasion using compliant contact wheels.

II. METHODOLOGY

A. DOE Methodology

This study uses the 2^k full factorial DOE method to screen the effects of tool pressing force, tool rotational speed (spindle speed), feed rate, workpiece geometry, tool hardness and tool types (flat and serrated contact wheels) towards the output of material removal volume, average material removal depth, and surface roughness in the form of R_a and R_z. Table 1 tabulates the factors and their respective level values accordingly within this study.

Table 1. Selected factors and their respective level values

Factor	Low	High
Tool Pressing Force (N)	20	40
Spindle Speed (rpm)	2400	3600
Feed Rate (mm/s)	5	10
Workpiece Geometry	Flat	Convex
Tool Hardness (Durometer)	40	65
Tool Type	Flat	Serrated

Various considerations were being used to justify the selection of factors as shown in Table 1, since including a wider range of factors can increase the number of experiments exponentially. The first set of factors deemed to be commonly and readily adjusted within any processes are the tool pressing force, spindle speed and feed rate, which will be integrated within the trials. On the other hand, the second set of factors refers to those that are not regarded as easy or readily to be adjusted within a surface finishing processes, which include workpiece geometry, tool (contact wheel) hardness, tool type (flat/plain surface to serrated, other customized shapes, etc.), tool geometry (diameter and width of wheel, serration angle if any, etc.), tool backing and workpiece material, abrasive type (material, grit size, grit design, etc.) and abrasive backing weight.

However, it is not possible to include all of the factors within the second set due to time and material constraints, as well as effectiveness of including them. For example, contact wheels, workpieces and abrasives come in various geometries and materials with various specifications. In most cases, these specifications are often undisclosed and/or subjected to the approval of the manufacturer, in the case of contact wheels and abrasives. Hence, it was deemed sufficient to provide a representation for geometrical differences for workpiece in the form of 2 types of surfaces (flat and convex), as well as material and geometrical differences in contact wheels in the form of hardness and types, respectively.

For the output selection, material removal volume and depth were deemed to be useful for processes that require fine tolerance in material thickness after surface finishing, since there is unlikely any accurate correlation between the two available yet from literature. Furthermore, these output parameters are quintessential in the manufacturing sector within the aerospace industry. For processes that require specified surface roughness values for a specific engineering purpose, the common output parameters R_a and R_z were deemed appropriate to be included in as a result of their common usage.

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Subsequently, the results were then tabulated within Microsoft Excel and fed into the statistical software Minitab 18, to determine the effects of the parameters in the form of Main Effects Chart, Pareto Chart of the Effects, Interaction Plots and Regression Equations.

B. Experimental Setup

A representative setup for the experiment is shown in Fig. 1a. Contact wheels of 2 types shown in Fig. 1b were coupled with an RS90 spindle installed at the end effector of the ABB robot IRB6660 M2004. The elastic portion of the contact wheels with a thickness of 18.8 mm were made of Neoprene material, with outer diameters of 101.6 mm and width of 38.1 mm. The land-to-groove ratio for the serrated wheels is 1:1 with a 45° angle. 3M Trizact abrasive belts with grit size graded A45 and 237AA cloth backing were pasted with adhesive tapes (3M ScotchTM) on the contact wheels during the material removal experiments. Aluminum 6061-T6 bars were milled to produce flat and convex workpieces, with the convex workpieces having 120 mm radius of curvature.

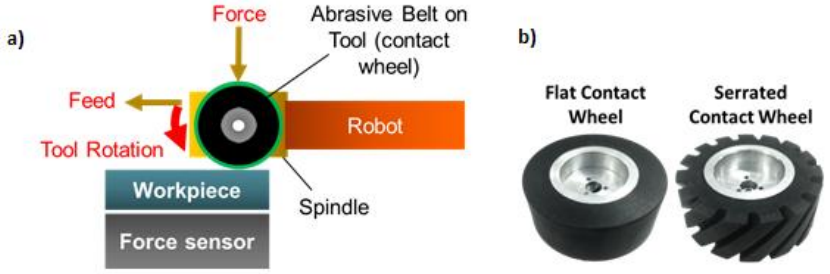

Fig. 1 a), Representative setup for material removal experiment and b), contact wheels

For each run, the spindle of the wheel begins to run at the programmed speed and then exerts a vertical downward force down onto the workpiece. The force was validated through an AMTI MC6-1000 six-axis transducer force sensor placed directly below the workpiece. Abrasion was done in a straight toolpath of 20 mm length each where the direction of feed was perpendicular to the rotational axis of the wheel. In the case of the convex workpiece, the toolpath used was parallel to the length of the workpiece 'cylinder'. After each trial, they were marked and a fresh workpiece was prepared for the next trial.

Measurements for material removal volume and depth were done with an optical surface profilometer Keyence VR-3100, where scanned examples are shown in Fig. 2. For each trial, a sample of 10mm length approximately within the middle portion of the abraded surface was extracted for analysis. This portion, also known as the steady-state segment, will represent a more accurate data when doing comparison between the runs as each run experiences different damping effects during the initial portion of the toolpath, which cannot be compared between each run and may represent incorrect data.

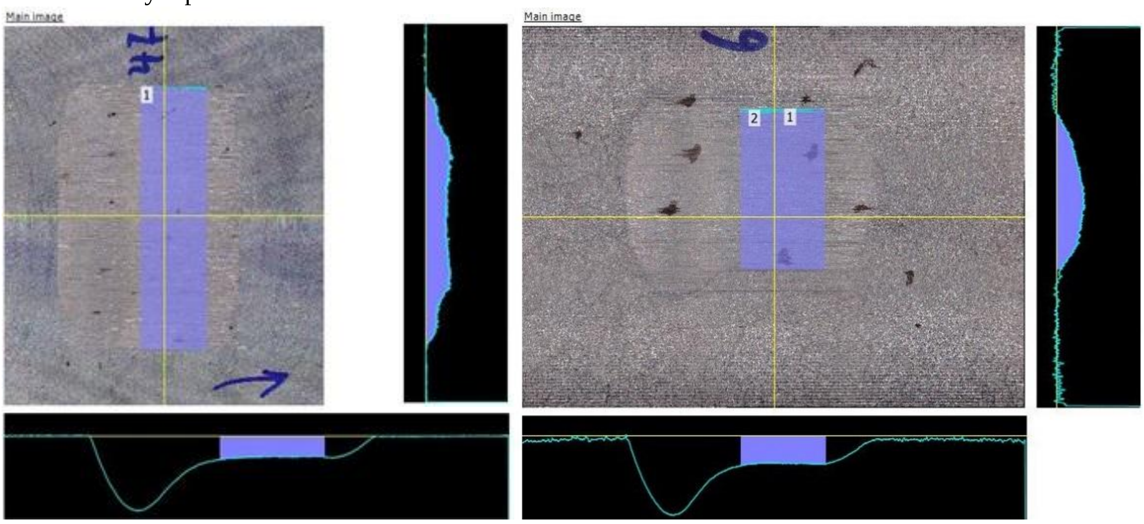

Fig. 2 Extraction of surface properties from scanned surfaces (flat and convex surfaces for left and right, respectively)

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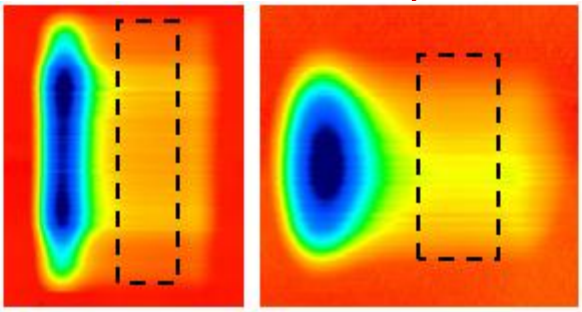

Fig. 3 Scanned colour representation of the material removal patch in Fig. 2, with red and blue colour representing highest and lowest regions, respectively. Depth and volume measurements are within the dashed markings

On the other hand, measurements for surface roughness R_a and R_z were done with a surface roughness tester Mitutoyo Surface Roughness Tester SJ-301 with tip radius of 5µm angled at 90°. To ensure that the data is accurate, a gauge block was used to calibrate the stylus and proper methodological procedures for measurements were taken from ISO 3274, ISO 4287 and ISO 4288.

III. RESULTS

A. Determining Significant Factors and Interactions

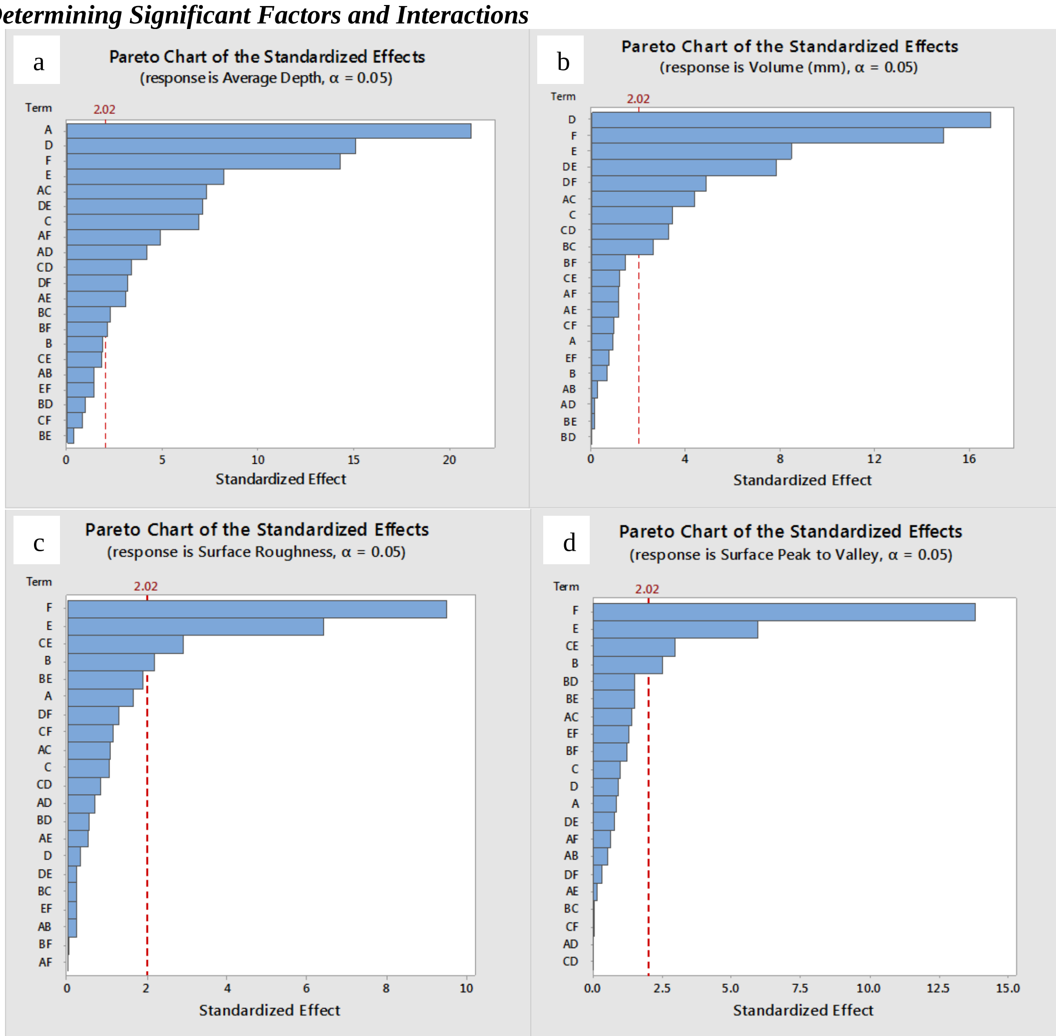

Fig. 4 Pareto Chart of the Standardized Effects for a) average depth, b) volume, c) R_a and d) R_z

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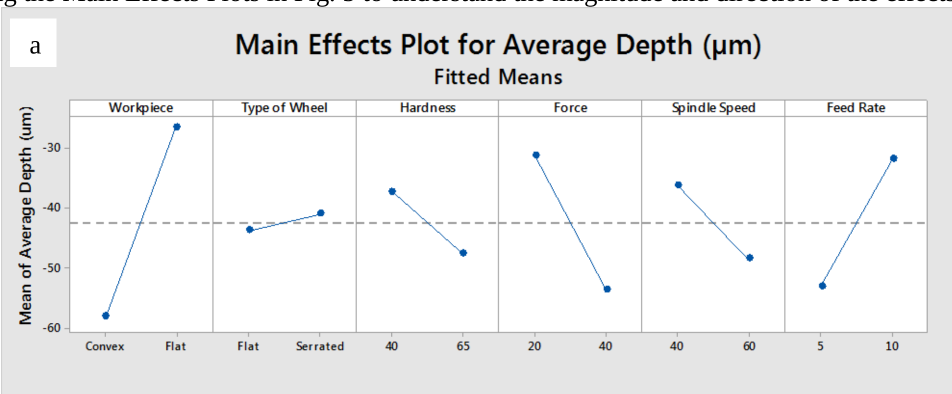
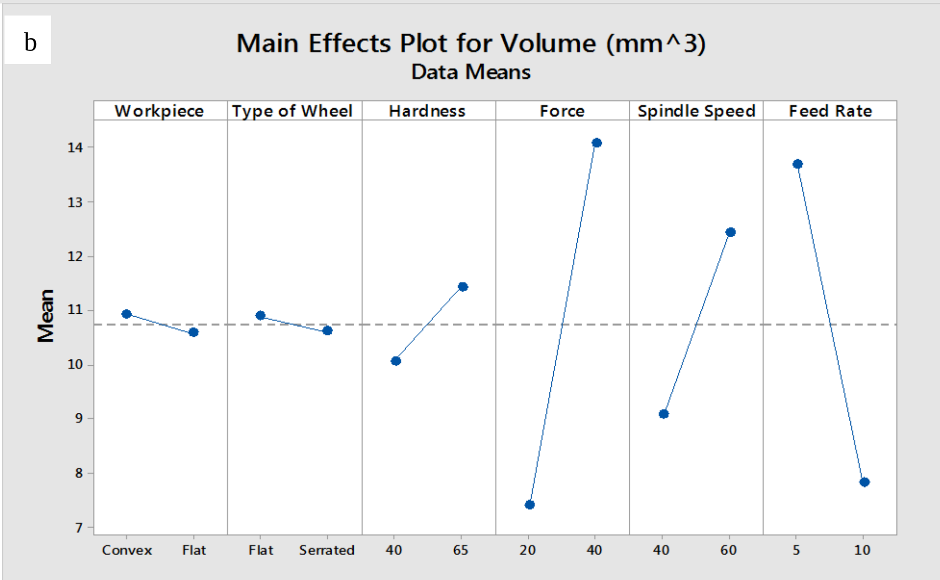
Table 2. Allocation of terms to each factor

Term	Factor	Term	Factor
A	Workpiece Type	D	Force
B	Type of Wheel	E	Spindle Speed
C	Hardness	F	Feed Rate

From the charts in Fig. 4 and with regards to material removal, both graphs (Fig. 4a and 4b) are complimentary and highlight force, feed rate, spindle speed and hardness as factors that have significant effects in the order of descending magnitude on the output. It is also important to note that the input factor A (type of workpiece) is highlighted as the factor that influences the average depth the greatest. For the output of average depth, the interactions with significant effects are namely AC, DE, AF, AD, CD, DF, AE, BC and BF, while for volume, they are DE, DF, AC, CD and BC. With regards to the non-significant factors, both outputs have minimal effects from the type of wheel used, while the type of workpiece also has a minimal effect on the volume of material removed. On the other hand, for surface roughness, both charts show similar trends with feed rate providing the most effect, followed by the spindle speed and the type of wheel. The interaction between hardness and spindle speed (CE) is also significant. With regards to the non-significant factors, both outputs have minimal effects from the type of workpiece, tool hardness and force.

From all of the aforementioned outputs, it should be noted that factors that are not significant on their own can also have significant effects within interactions with other factors. For example, the type of workpiece used alone may not have any significant effects on the volume of material removed, but coupled with hardness, the interactions between both can be quite significant. After understanding the significance of the main factors, they are further studied using the Main Effects Plots in Fig. 5 to understand the magnitude and direction of the effects.





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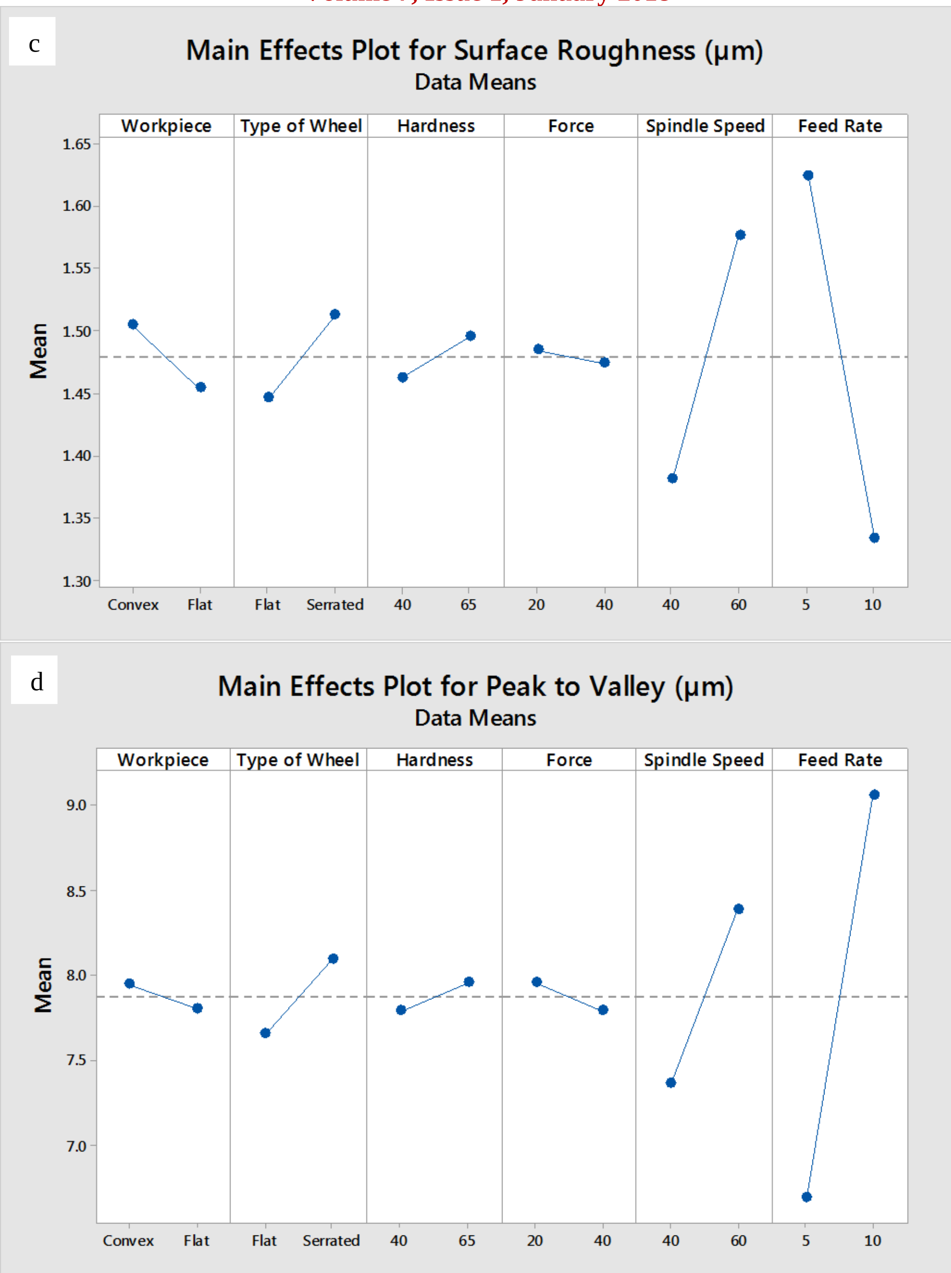

Fig. 5 Main Effects Plots for a) average depth, b) volume, c) R_a and d) R_z

For material removal, increase in force and spindle speed result in increased volume removed and average depth, whereas an increase in the feed rate decreases the volume removed and the average depth. Due to the nature of the workpiece, the average depth of the contact patch with the convex workpiece are generally deeper compared to the flat workpiece? With regards to the surface roughness, an increase in the spindle speed increases both R_a and R_z values. However, increasing the feed rate results in a lower R_a but results in an increase R_z values.

After the individual effects have been studied, Interaction Plots in Fig. 6 are used to show the relationship between factors and the magnitude of the effect on the output with its interaction. The magnitude of the effect of the interaction is shown by how non-parallel the lines are i.e. the greater the strength of interaction, the lesser the parallelism.

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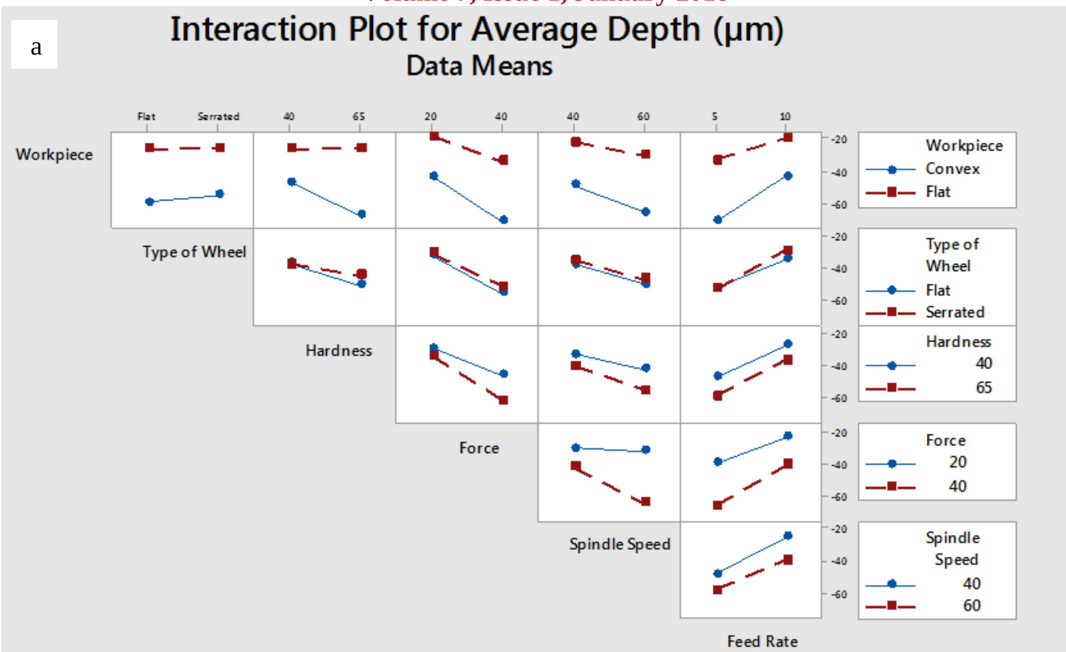

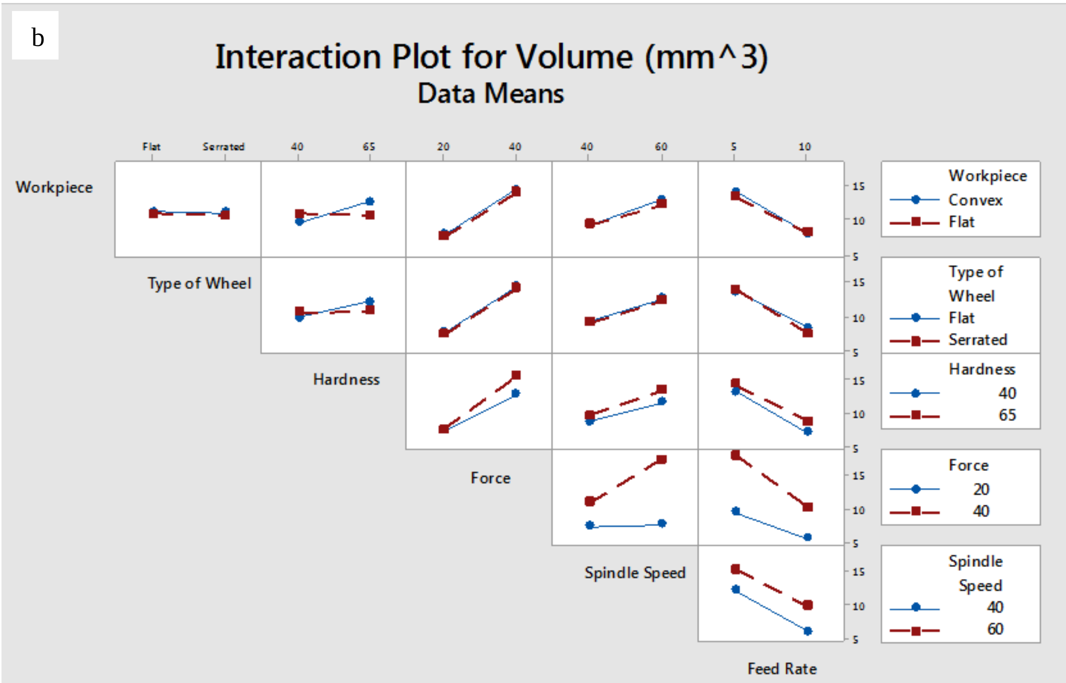

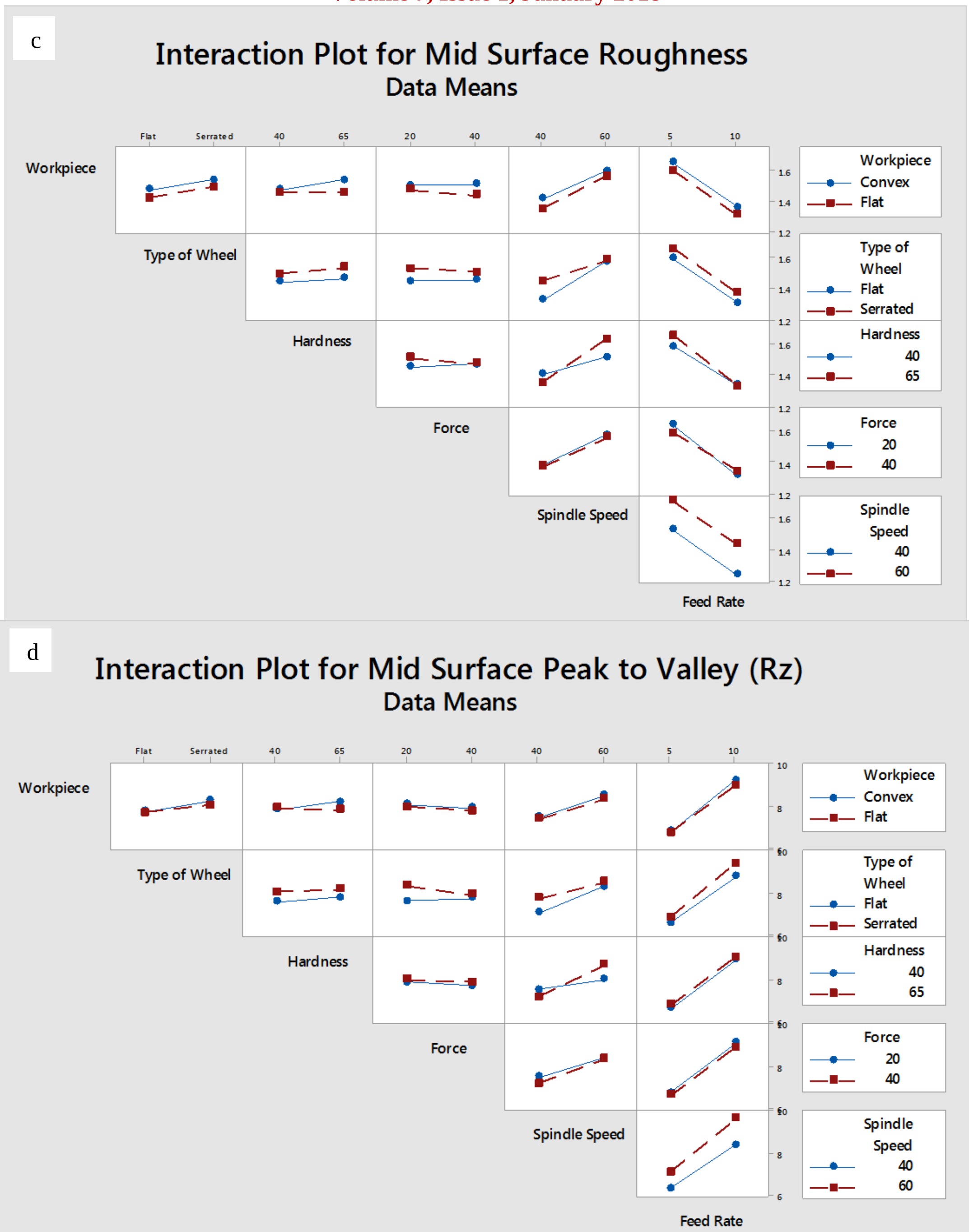

Fig. 6 Interaction Plots for a) average depth, b) volume, c) R_a and d) R_z

As mentioned earlier, the greater the strength of interaction, the lesser the parallelism. Referring to the Pareto Charts in Fig. 4, the highest interactions for average depth and volume are AC and DE, respectively, and CE for both R_a and R_z. When cross-referencing the aforementioned observations with the interaction plots in Fig. 6, it can be seen that AC, DE and CE poses one of the highest non-parallelism. Furthermore, in Fig. 6, it should be seen that factors that are not significant on their own can also have significant effects within interactions with other factors, shown in the interactions of BC and AC in the outputs of average depth and volume, and CE for both R_a and R_z.

B. Regression Equations

In this section, estimates of the output can be obtained via the regression equations generated. Below are the regression equations in uncoded units for the respective output parameters. It should be noted that better regression

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equations can be obtained with increasing the levels and range of factors, hence the equations below are for estimation purposes only.

To Minimize:

Surface Roughness (R_a) = 2.089 - 0.036A + 0.190B - 0.00905C + 0.0008D - 0.00863E - 0.0591F - 0.0034 A*B + 0.00132 A*C + 0.00106 A*D - 0.00081 A*E + 0.00012 A*F + 0.00030 B*C - 0.00084 B*D - 0.00291 B*E - 0.00025 B*F - 0.000103 C*D + 0.000353 C*E - 0.000560 C*F - 0.000038 D*E + 0.000788 D*F + 0.000137 E*F

Peak to Valley (R_z) = 9.46 - 0.700 A + 0.959 B - 0.0947 C - 0.0332 D - 0.1132 E + 0.297 F + 0.0473 A*B + 0.00971 A*C + 0.00030 A*D + 0.00161 A*E + 0.0229 A*F - 0.00069 B*C - 0.01289 B*D - 0.01283 B*E + 0.0434 B*F - 0.000019 C*D + 0.002081 C*E - 0.00028 C*F + 0.000698 D*E - 0.00121 D*F + 0.00457 E*F

To Maximize:

Average Depth = -114.2 + 16.73 A - 13.91 B + 0.588 C + 1.868 D + 1.843 E + 2.46 F + 1.049 A*B- 0.4341 A*C - 0.3114 A*D - 0.2274 A*E + 1.472 A*F + 0.1350 B*C + 0.0731 B*D + 0.0252 B*E + 0.632 B*F- 0.02034 C*D - 0.01070 C*E + 0.0195 C*F - 0.05265 D*E + 0.0948 D*F - 0.0417 E*F

Volume Removed = 30.37 - 4.01 A + 3.03 B - 0.240 C- 0.420 D - 0.437 E- 0.619 F + 0.048 A*B + 0.0696 A*C + 0.0035 A*D + 0.0223 A*E - 0.0913 A*F - 0.0418 B*C + 0.0002 B*D - 0.0024 B*E - 0.1149 B*F + 0.00518 C*D + 0.00188 C*E + 0.00604 C*F + 0.01545 D*E - 0.03867 D*F + 0.00572 E*F

IV. CONCLUSION

This study was carried out to determine the selected factors using the DOE (Design of Experiment) method and their respective effects on the output parameters of material removal (volume and average depth) and surface roughness (R_a and R_z). The selected factors (force, spindle speed, hardness, feed rate, workpiece and type of wheel) were used to collect data on material removed as well as the surface roughness. The data were then analyzed using the MiniTab18 software to determine the main effects as well as the interactions between the input factors. It was found that for material removal, the main factor i.e. the type of wheel, was insignificant to both the average depth and the volume removed, while the type of workpiece is insignificant to the volume removed alone. However, all of the factors are significant in their interactions with each other. As for the surface roughness, the main factors of feed rate, spindle speed and type of wheel are significant to the output of R_a and R_z, while only the factor of hardness is significant within the interaction with spindle speed. Thus, from this study, the significant factors and interactions can be considered for future studies with other combination of factors not mentioned or selected within this study in the exploration of various effects on the interested outputs.

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