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Characterization of machining quality attributes based on spindle probe, coordinate measuring machine, and surface roughness data

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Abstract

This study investigates the effects of machining parameters as they relate to the quality characteristics of machined features. Two most important quality characteristics are set as the dimensional accuracy and the surface roughness. Before any newly acquired machine tool is put to use for production, it is important to test the machine in a systematic way to find out how different parameter settings affect machining quality. The empirical verification was made by conducting a Design of Experiment (DOE) with 3 levels and 3 factors on a state-of-the-art Cincinnati Hawk Arrow 750 Vertical Machining Center (VMC). Data analysis revealed that the significant factor was the Hardness of the material and the significant interaction effect was the Hardness + Feed for dimensional accuracy, while the significant factor was Speed for surface roughness. Since the equally important thing is the capability of the instruments from which the quality characteristics are being measured, a comparison was made between the VMC touch probe readings and the measurements from a Mitutoyo coordinate measuring machine (CMM) on bore diameters. A machine mounted touch probe has gained a wide acceptance in recent years, as it is more suitable for the modern manufacturing environment. The data vindicated that the VMC touch probe has the capability that is suitable for the production environment. The test results can be incorporated in the process plan to help maintain the machining quality in the subsequent runs.

Keywords: Machining quality; Coordinate measuring machine (CCM); Design of experiment (DOE); Vertical machining center (VMC); Dimensional accuracy; Surface roughness

1. Introduction

Discrete part production using a computer numerically controlled (CNC) machine tool is common in modern manufacturing. Depending on the accuracy and surface finish requirements, the machining parameters, which have a significant influence on part quality, need to be set properly. The machining parameters are an important part of process plan, which can be determined from user experience, test experiments, and relevant reference materials. Improperly set parameters may induce unwanted complications in machining. For instance, chatter represents uncontrollable, excessive vibration, which produces unacceptable surface quality [1]. Vibration in machining can be minimized through the use of computer simulation tools. Simulation can project the optimal range of cutting speeds and feed rates for a chatter-free machining, hence producing less scrap and enhanced part quality. Since each machine tool exhibits different characteristics, such as stiffness, damping ratio, and natural frequency, the importance of pre-machining simulation is applied to each machine. Especially when the machine is newly acquired, the machine characteristics need to be tested and ascertained. In this study, CutPro® milling simulation software accompanied by a hammer test was used to generate a set of vibration free-cutting parameters. However, the simulation results do not provide a comprehensive picture when several material types are machined at the same time with varying parameters. The significant factors and potential interactive effects need to be ascertained to achieve a high level of quality in machining.

Equally important in machining is the confidence in the measuring instruments, from which part quality characteristics are ascertained. Part dimensional accuracy check has been largely based on a post-process inspection, such as a coordinate measuring machine (CMM). The downside of this technique is that non-conforming parts can be produced between inspections. To remedy the problem, a machine mounted touch probe has started gaining a popularity, which has the similar working principles of CMM. The probe enables the measurement of machined parts, while they are still

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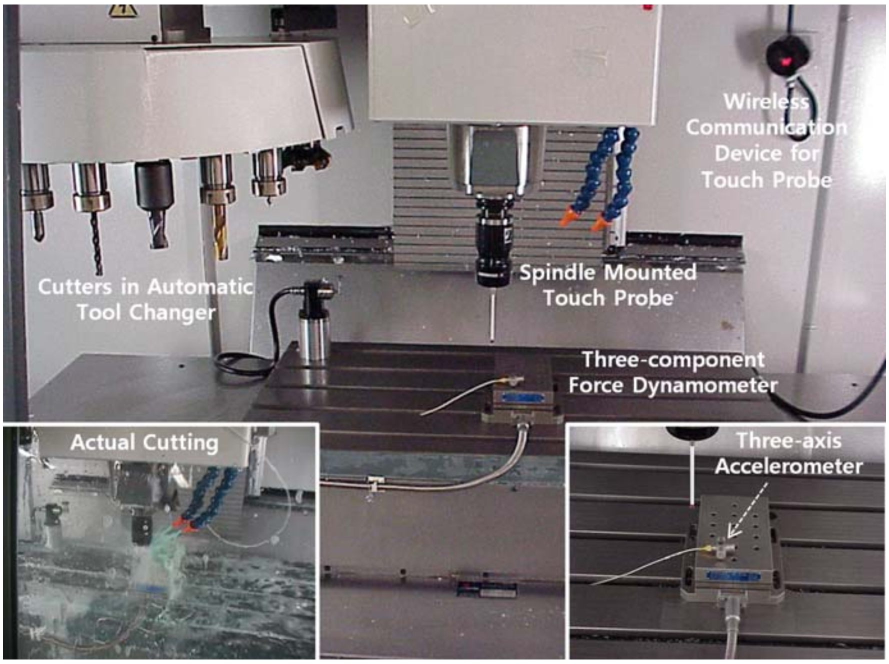


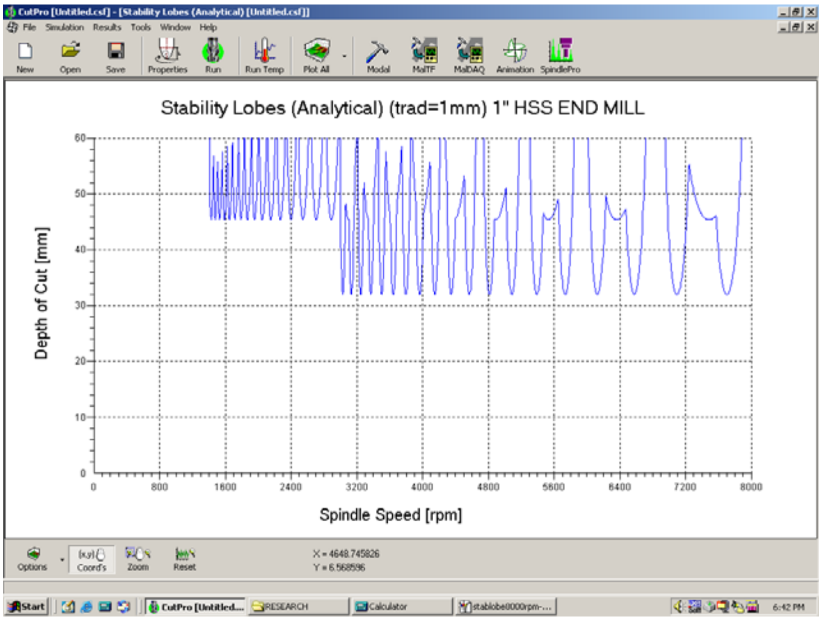
Figure 1. The experimental apparatus with the inlets showing the actual cutting and the accelerometer.

fixed on the machine (see Figure 1). By providing the part size or gauged information directly into a CNC controller, a closed-loop process control can be realized [2]. This is particularly important for a modern, computer controlled production environment, where a very little human intervention is expected during machining cycles. The accuracy of the probe, however, is affected by the machine tool's positional accuracy and positioning system. Therefore, the capability of the probe needs to be analyzed, and possibly, compared with the CMM measurements. CMMs are widely used in the manufacturing industry for precision inspection and quality control, and recognized as reliable and flexible gauges suitable for assessing the acceptability of machined parts [1, 2]. The comparison will offer insights towards the extent of measurement errors reflected on the touch probe. To characterize the machining quality attributes, a set of cutting experiments has been performed. The dynamic behavior of the machine tool structure was analyzed first to determine the range of chatter-free machining parameters (see Figure 2). During the actual cutting, the three-component force dynamometer continuously measured the X, Y, and Z directional cutting forces, while the three-axis accelerometer monitored and recorded the vibrations. The experimental data were analyzed, and it was found that the selected cutting parameters didn't induce any excessive vibrations or force signals. This vindicates that the cutting was conducted in a chatter-free condition. In this study, the tool wear effect was not considered in the DOE model, because an artificially induced tool wear couldn't be set for each cutting condition. In this study, the main contribution is as follows. Prior to the machining, an analytical test was performed to identify the stable, chatter-free machining conditions, and the DOE was conducted under the condition. Two critical machining quality characteristics are measured for three most common material types, and the most influential machining parameters were found, which would serve as a decision criterion for the subsequent process planning. In addition, the bore size was measured using two different gauges. The machine mounted touch probe acts as an online inspection tool, while the CMM is used for the post-process gauging. The readings from two types of gauges were compared to verify that which machining parameters have the most influence on the bore diameters. The findings from this study are expected to help develop a computerized process plan, which will be a mainstay of future production systems. The overall structure of this study is as follows. The first section is the introduction, delineating the purpose and the importance of the study. The second section illustrates the details of cutting experiments, while the third section elaborates on the data analysis. The conclusion is drawn in the fourth section.

2. Descriptions on cutting experiments

In this study a newly acquired, state-of-the-art Cincinnati Hawk Arrow 750 Vertical Machining Center (VMC) was used to conduct the DOE. Cutting experiments allow the production engineers to adjust the settings of the machine in a systematic manner and to learn which factors and interaction effects have the greatest impact on the part quality before the machine is put to use for production. This step is necessary, because in metal cutting, most process control models are based on the empirical data and no universal mathematical models exist [3-5].

In this study, three factors are selected. The levels of the



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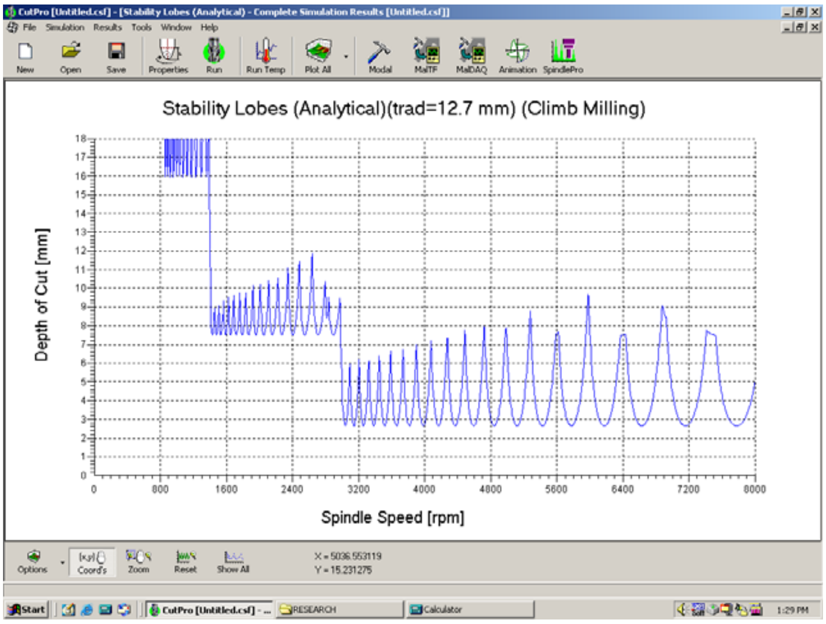


(b)

Figure 2. Analytical stability lobes for the VMC: (a) radial depth of cut 1mm, (b) radial depth of cut 12.7 mm.

Hardness factor have three material types that are widely used in both automotive and aerospace industry: 6061-T6 aluminum, 7075-T6 aluminum, and ANSI-4140 steel. The Speed and Feed factors established using the CutPro® software are correlated with the appropriate material (as illustrated in Table 1). A set of Kistler® impulse force hammer and accelerometer is used to determine the frequency response function (FRP) of the machine tool structure, while an 1-inch end mill cutter is fixed in the spindle (see Figure 3). This impulse force testing determines the dynamic response of the VMC, from a force pulse generated by the impact of a hammer and the response signal measured with an accelerometer. The FRF is an input CutPro® module for modal analysis to obtain the analytical stability lobes for chatter avoidance during machining. The stability lobe graph generated by the CutPro® Software provides the combination of depth of cut and cutting speed. Consequently, the axial and radial depth of cut and cutting speed were tuned for a chatter-free machining.

During the machining, the vibration and cutting force data are collected using the vibration sensor (Kistler tri-axial ac-

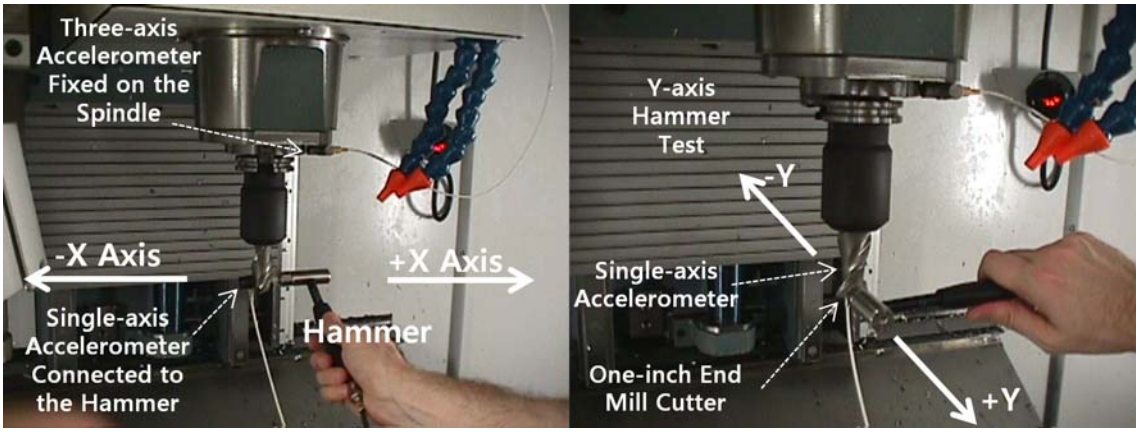


Figure 3. Hammer tests on Arrow 750 VMC for X-axis and Y-axis.

celerometer, ±500g, sensitivity: 10mV/g) and the force dynamometer (Kistler 9257B, sensitivity: -16 ~ -33 pC/lb). The number of sampling points was 5000 for the record length of 1 second. Representative sensor signals for vibration and cutting force are given in Figures 4 and 5, respectively, for AISI 4140 steel. Since the steel is much harder than the aluminum blocks, the stability of sensor signals are very important during the experiment. The graphs show that the cutting was very stable. In the figures, the top window indicates channels 0 and 1 that correspond to X and Y directions of the cut, while the bottom window indicates channels 1 and 2 that correspond to Y and Z directions of the cut.

Each machined block has two stepped bores (65 and 50-mm diameters). The bores were selected as the critical quality characteristics. In fact, the circularity and the cylindricity of machined parts constitute some of the most fundamental geometric features in engineering [6, 7]. The block design was carried out with the Solidworks 3-D design tool (see Figure 6). The file of the drawing was transferred to Feature Cam, which converts 3-D drawings into G & M codes (CNC instructions) for the VMC. To measure the surface roughness, four readings were taken on each diameter for a total of eight readings for each replicate. To measure the each bore diameter, four points that are 90 degrees apart and about a half way along the bore depth are selected. The spindle mounted touch probe was programmed to measure the bore size automatically. After that, the machined block was transferred to the Mitutoyo B403B CMM, and the same spots were measured. Therefore, a total of 16 readings were made to compare the bore size. To ensure the proper functioning of round parts, permissible deviations from a true circle are allowed in the form of tolerance zones bounded by two concentric circles, which dictate the desired dimensional and form accuracy [6, 7]. The bores had a tolerance of -0.1 mm, corresponding to the ISO tolerance grade of IT10. Tolerances were measured using the

Table 1. Feed and speed levels.

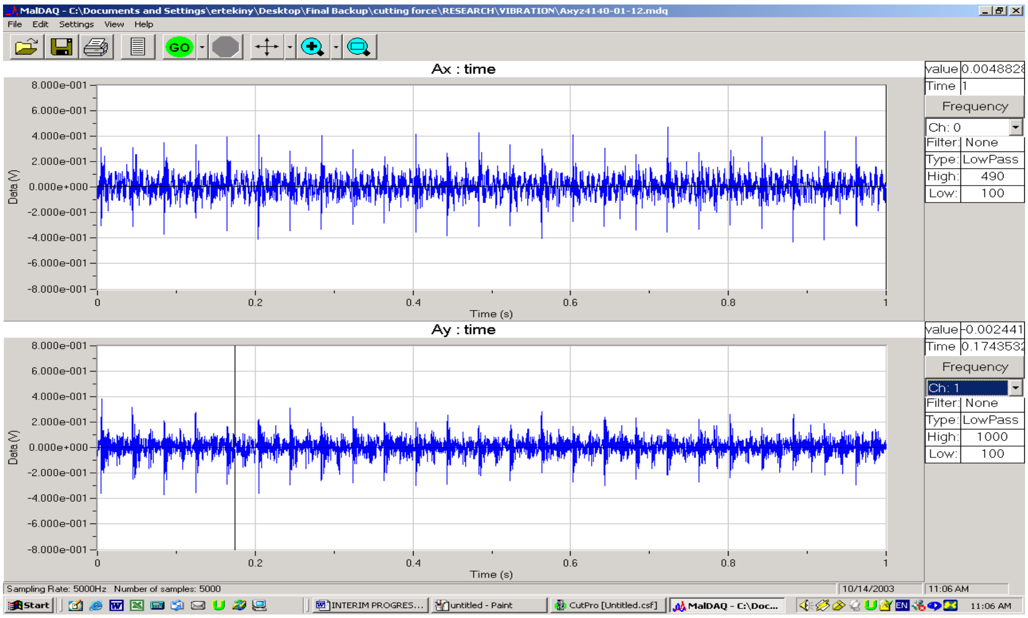
Material	Feed	Speed
6061 Al	127 mm/min (-1)	1250 rpm (-1)
6061 Al	254 mm/min (0)	2500 rpm (0)
6061 Al	381 mm/min (+1)	3750 rpm (+1)
7075 Al	127 mm/min (-1)	1250 rpm (-1)
7075 Al	254 mm/min (0)	2500 rpm (0)
7075 Al	381 mm/min (+1)	3750 rpm (+1)
4140 Al	50.8 mm/min (-1)	750 rpm (-1)
4140 Al	127 mm/min (0)	1500 rpm (0)
4140 Al	254 mm/min (+1)	2250 rpm (+1)

Table 2. Factors and levels.

	Factors		
Level	Hardness	Speed	Feed
Low (-1)	6061 Aluminum	Slow	Slow
Center (0)	7075 Aluminum	Mid	Mid
Upper (+1)	4041 Steel	Fast	Fast

Table 3. Rockwell hardness readings for machined blocks from DOE.

Block No.	First Average	Second Average
1-1	52.7	51.9
2-1	96.3	95.3
3-1	81.4	87.5
4-1	95.6	91.8
5-1	86.5	84.6
6-1	50.2	46.6
7-1	85.1	89.5
8-1	93.7	94.1
9-1	44.0	47.0
1-2	49.6	43.9
2-2	97.4	92.4
3-2	82.6	84.7
4-2	95.5	82.3
5-2	95.1	87.2
6-2	50.2	49.0
7-2	76.5	87.1
8-2	91.8	94.6
9-2	45.2	50.6



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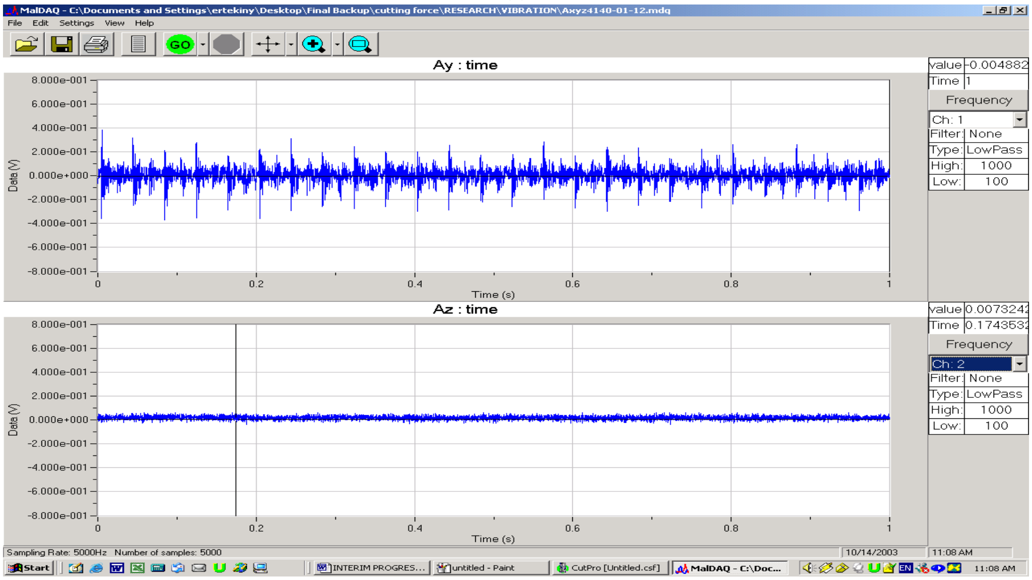


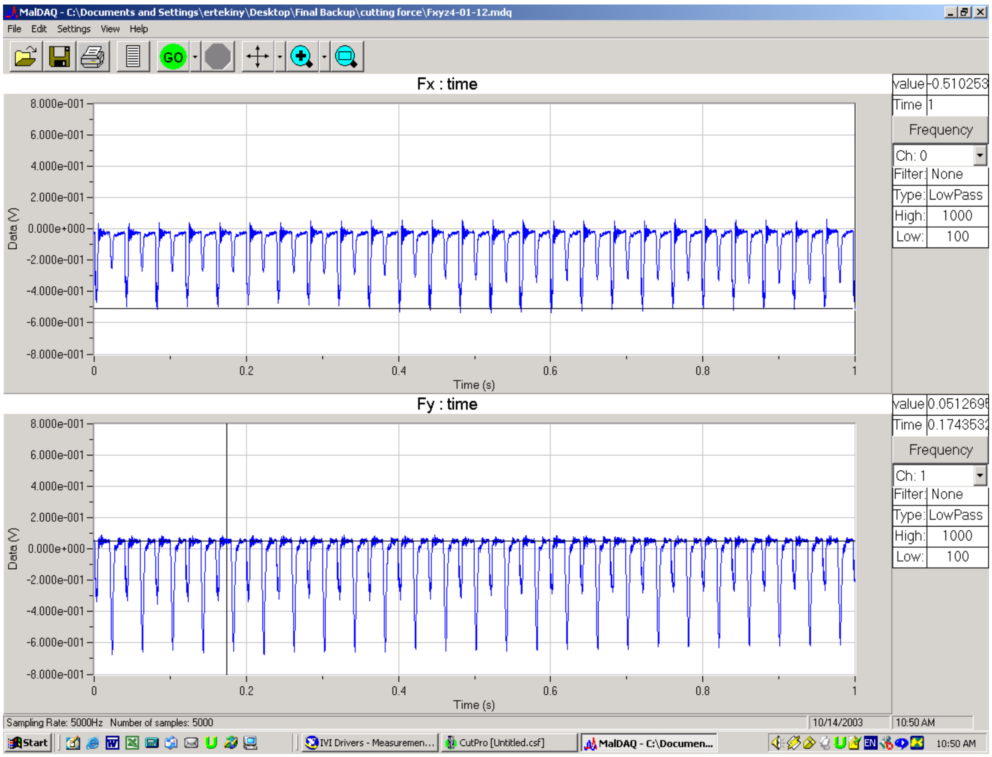
(b)

Figure 4. Spindle vibration (acceleration) sensor signature for AISI 4140 steel (cut number 1).

touch probe and the CMM.

The Fractional Factorial Design was implemented in this experiment to minimize the total number of runs and to ensure that there was no significant impact on output. A Full DOE design for this experiment would have consisted of three factors containing three levels each, as indicated in Tables 1 and 2. In this setting, two replicates that would have required 54 metal blocks (runs), whereas the fractional factorial formula reduced the time and costs by 33.3% by using: (33-1) x (2 replicates) = 18 runs. The actual DOE design matrix was generated with Statistica. In order to eliminate a potential bias during the milling, randomization of the run order was implemented. To measure the hardness values, three points on the shoulder (i.e., a flat, ring surface between two bores) that are 120 degrees apart have been randomly selected. The readings are averaged, and also repeated twice to get the representative hardness readings. The overall average values of three material types are 43.2 for 6061 Al, 84.5 for 7075 Al, and 92.4 for 4140 Steel. Table 3 indicates the Rockwell hardness readings.

The hypothesis was that all factors have an equal effect on milling operations and on dimensional quality. Therefore, a null hypothesis was set as: H0: $\mu 0 = \mu 1 = \mu 2 = 0$. If there was one or more factors that have a significant effect, the null hypothesis would be rejected, and an alternative hypothesis would be accepted: H1: $\mu 0 \neq \mu 1 \neq \mu 2 <> 0$. To allow the 95% certainty, the confidence level was set at $\alpha = 0.05$.



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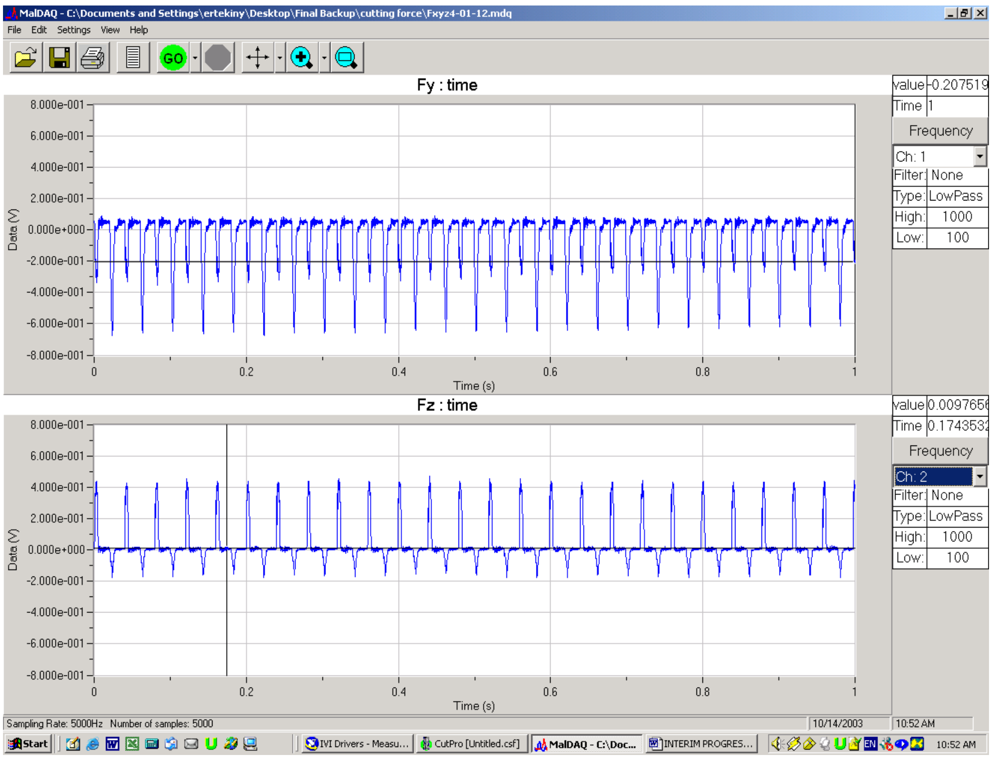

(b)

Figure 5. Cutting force sensor signature for AISI 4140 steel (cut number 1).

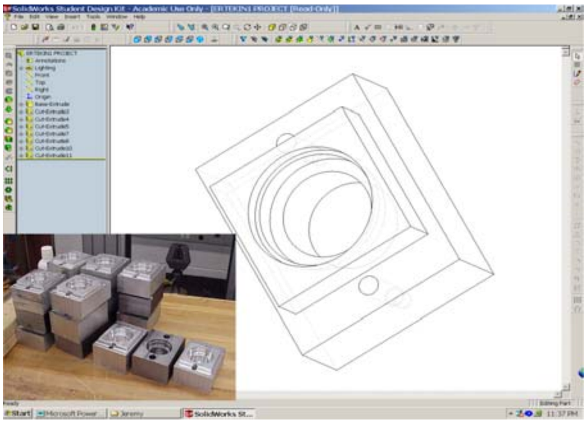

Figure 6. Solidworks 3-D drawing of blocks with the inlet showing the machined blocks.

3. Data analysis

3.1 Dimensional accuracy

Prior to utilizing the CMM for the post-process measurements of the machined blocks, a process capability study was performed using a standard ball. The ball was measured by the same operator, using a series of processes that entailed measuring points along the circumference. A total of ten measurements were taken for each of the two established patterns of 4 and 8 points. The natural tolerance was determined by establishing the standard deviation for each point pattern that calculated to the 3-sigma value. An average for the three point patterns was determined to be 0.000248 inch. When the natural tolerance was compared to the manufacturer's standard tolerance of 0.0003 inch, the determination was made that the CMM was operating within the proper tolerance range. A process capability analysis was also performed for the probe. After the measurement data have been collected from the touch probe and the CMM, these data were treated by the following procedures before performing the DOE analysis. First, the touch probe and CMM measurement data were entered in Minitab for quality analysis. The 50-mm and 65-mm bore diameter data were processed independently to analyze the data integrity and the results are presented in Figures 7 and 8. The comparison of both CMM and probe range charts indicated that blocks 13 and 17 had an abnormal amount of variations between the two measurement methods for both diameters. In addition, the CMM process capability indicated that the data have a consistent downward shift. The Cp value indicated that the CMM process would be within 1.03 times 6σ. There was no discernable cause for these abnormalities. Second, the process capability was calculated on the 50-mm and 65-mm diameter data to confirm the process consistency.

The CMM and Probe data were treated as a subgroup to enable the between and within capability, and to obtain a result that would give indications about the overall process. Evaluation of the process capability for both diameters illustrates that the Cp values of 1.48 (50-mm) and 1.44 (65-mm), both of which are not out of control. The probability curves indicated a normal curved shape. The overall results suggest that the process was performing within a reasonable proximity of normal, but the specification spread is expected to be beyond 6σ. The data were also entered into Statistica for the factorial analysis. The bore diameter data were processed independently and the results are presented in Tables 4 through 7. The ANOVA tables on the 50-mm revealed that the CMM had the significant interaction effect of factors Hardness + Feed, while the ANOVA table on the Probe had the significant factor of Hardness and the interaction effect of Hardness + Feed. The ANOVA tables on the 65-mm revealed that the CMM had the significant factor of Hardness and Feed, while the interaction effect was Hardness + Feed. The ANOVA table for the Probe revealed that the significant factor of Hardness and the interaction effect of Hardness + Feed.

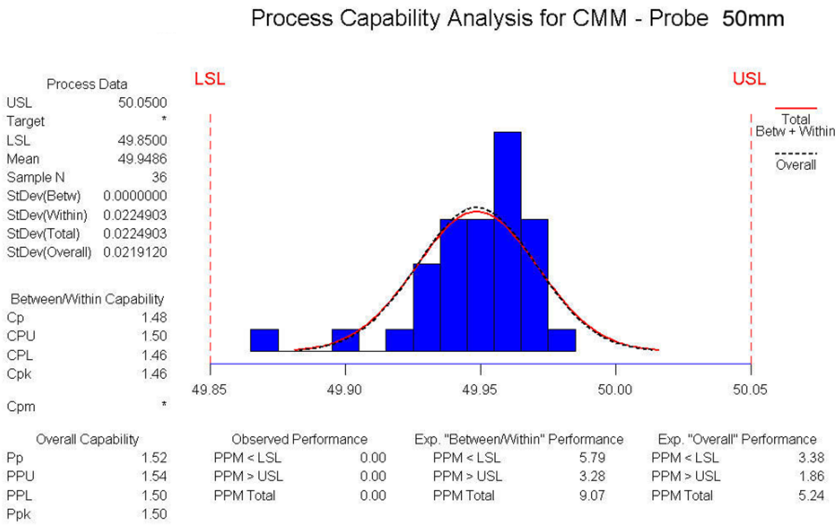

Figure 7. Process capability analysis for CMM-Probe (50 mm bore).

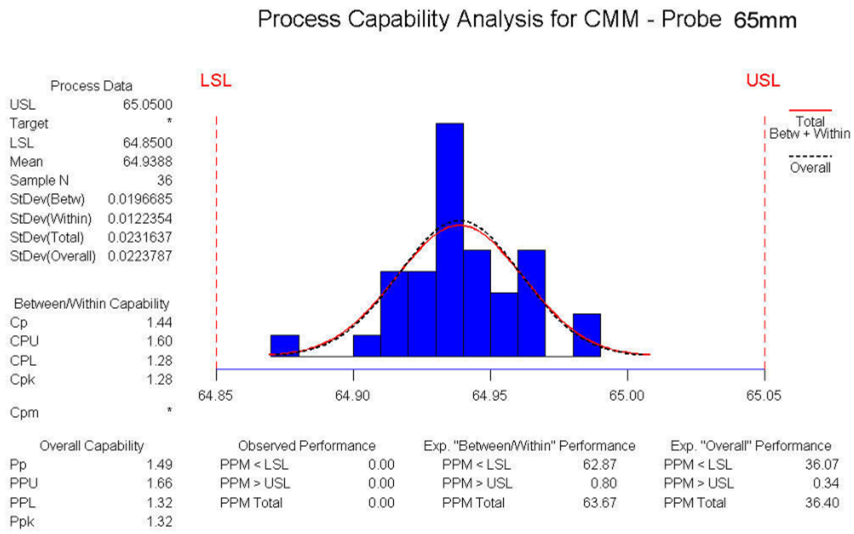

Figure 8. Process capability analysis for CMM-Probe (65 mm bore).

Table 4. 50-mm CMM ANOVA table.

Factors	SS	df	MS	F	P
Blocks	0.000109	1	0.000109	1.128619	0.319085
(1) Hardness(L)	0.000073	1	0.000073	0.752583	0.410925
Hardness(Q)	0.000043	1	0.000043	0.442882	0.524454
(2) Feed (L)	0.000272	1	0.000272	2.825558	0.131282
Feed(Q)	0.000481	1	0.000481	4.991952	0.055923
(3) Speed (L)	0.000043	1	0.000043	0.446908	0.522624
Speed (Q)	0.000121	1	0.000121	1.258642	0.29445
1L by 2L	0.000552	1 *	0.000552	5.722203*	0.043711*
1L by 2Q	0	1	0	0.003667	0.953196
Error	0.000771	8	0.000096		
Total SS	0.002462	17			

*ANOVA; Var.:CMM_DV; R-sqr = .68662; R-adj = .33407 (50_data.sta) 3 3-level factors, 2 Blocks, 18 Runs; MS Residual = .0000964.

Table 5. 50-mm Probe ANOVA table.

Factors	SS	df	MS	F	P
Blocks	0.001571	1	0.00157	4.995113	0.055862
(1) Hardness(L)	0.002024*	1*	0.002024*	6.434182*	0.034897*
Hardness(Q)	0	1	0	0.000447	0.983647
(2) Feed (L)	0.000097	1	9.70E-05	0.307023	0.594658
Feed(Q)	0.000228	1	0.00023	0.724981	0.419271
(3) Speed (L)	0.000224	1	0.00022	0.712984	0.422985
Speed (Q)	0.00013	1	0.00013	0.412604	0.538619
1L by 2L	0.000159	1	0.00016	0.504393	0.497753
1L by 2Q	0.001719*	1*	0.001719*	5.464627*	0.047590*
Error	0.002516	8	0.00032		
Total SS	0.008736	17			

*ANOVA: Var.:PROBE_DV; R-sqr = .712; R-adj = .388 (50_data.sta) 3 3-level factors, 2 Blocks, 18 Runs; MS Residual = .0003145

Table 6. 65-mm CMM ANOVA table.

Factors	SS	df	MS	F	P
Blocks	0.000116	1	0.000116	5.131	0.053291
(1) Hardness(L)	0.002502*	1*	0.002502*	110.4093*	0.000006*
Hardness(Q)	0.000051	1	0.000051	2.2348	0.173292
(2) Feed (L)	0.000424*	1*	0.000424*	18.7039*	0.002530*
Feed(Q)	0.000037	1	0.000037	1.6115	0.239957
(3) Speed (L)	0.00001	1	0.00001	0.4394	0.526029
Speed (Q)	0.000613*	1*	0.000613*	27.0372*	0.000823*
1L by 2L	0.000017	1	0.000017	0.7357	0.415987
1L by 2Q	0.001439*	1*	0.001439*	63.5085*	0.000045*
Error	0.000181	8	0.000023		
Total SS	0.006844	17			

*ANOVA: Var.:CMM_DV; R-sqr = .97351; R-adj = .9437, 3 3-level factors, 2 Blocks, 18 Runs; MS Residual = .0000227

Table 7. 65-mm Probe ANOVA table.

Factors	SS	df	MS	F	P
Blocks	0.000756	1	0.000756	4.99673	0.05583
(1) Hardness(L)	0.002347*	1	0.002347*	15.50766*	0.004308
Hardness(Q)	0	1	0	0.00235	0.963506
(2) Feed (L)	0.000055	1	0.000055	0.36453	0.563723
Feed(Q)	0.000158	1	0.000158	1.04375	0.336849
(3) Speed (L)	0.000001	1	0.000001	0.00511	0.944744
Speed (Q)	0.000059	1	0.000059	0.3912	0.549091
1L by 2L	0.00007	1	0.00007	0.46309	0.515392
1L by 2Q	0.001968*	1*	0.001968*	13.00280*	0.006922*
Error	0.001211	8	0.000151		
Total SS	0.008795	17			

*ANOVA: Var.: PROBE_DV; R-sqr = .86234; R-adj = .70747, 3 3-level factors, 2 Blocks, 18 Runs; MS Residual=.0001513

Table 8. DOE block measurements for surface roughness.

WP	50 mm				65mm			
No.	X+(Ra)	X-(Ra)	Y+(Ra)	Y-(Ra)	X+(Ra)	X-(Ra)	Y+(Ra)	Y-(Ra)
1-1	0.61	0.68	0.65	0.58	0.54	0.71	0.56	0.56
1-2	0.58	0.62	0.57	0.73	0.68	0.64	0.68	0.75
2-1	0.74	0.72	0.71	0.82	0.80	0.89	0.89	0.85
2-2	1.10	1.58	1.21	0.84	1.06	1.24	0.93	1.02
3-1	0.58	0.58	0.58	0.76	0.65	0.55	0.61	0.65
3-2	0.68	0.66	0.63	0.58	1.02	1.33	0.93	0.64
4-1	0.74	0.80	0.68	0.71	0.72	0.68	0.83	0.72
4-2	1.15	0.95	0.98	1.28	1.04	1.07	1.13	1.26
5-1	0.61	0.55	0.63	0.55	0.58	0.55	0.61	0.64
5-2	0.51	0.52	0.85	0.57	1.10	0.94	1.07	1.10
6-1	0.53	0.55	0.52	0.55	0.53	0.55	0.54	0.64
6-2	0.70	0.84	0.71	0.64	0.84	0.86	0.70	0.85
7-1	0.60	0.57	0.66	0.60	0.70	0.62	0.68	0.58
7-2	0.78	0.54	0.58	0.58	0.89	0.96	0.99	0.86
8-1	0.51	0.65	0.68	0.77	0.58	0.53	0.55	0.66
8-2	0.89	0.86	1.11	0.99	0.81	0.73	0.85	0.80
9-1	0.62	0.59	0.58	0.71	0.61	0.67	0.65	0.59
9-2	0.70	0.83	0.75	0.75	0.93	0.95	0.99	1.11
Order Ckd	1	2	8	5	4	3	7	6

* RA 0.8 x 5 um; Calibrated to Std. of 2.95 um at 2.5 x5

* Checked calibration twice while recording measurements

3.2 Surface roughness

For surface roughness, the analysis of the experiment was run on Statistica. The surface roughness measurement data are shown in Table 8. Two runs were selected for operating parameters to create two blocks. Blocking reduces the variability in the response (DV: dependent variable) due to other external factors that are not considered. Eighteen replicates were created. ANOVA and 3-D charting of the independent variables (Feed, Speed, and Hardness) versus DV shows that Speed (RPM) is the most significant factor followed by Feed. Varying the Speed will significantly affect the desired surface finish, while Feed can be varied without affecting surface finish as significantly as Speed would. Reducing Feed will reduce surface finish readings. Further analysis would show that whether the material hardness has a significant effect on the surface finish. The most significant factor is noted to be Speed with the P-values of 0.0036 and 0.012. The P-value below 0.05 is considered to be a significant effect on the outcome. The P-value of 0.055 shows that Feed is not a significant factor, although it has an effect on the outcome. The 3-D plot of Feed and Hardness shows that a low feed rate combined with a high harness of material gives the better surface finish. This scenario will not produce the desired effect—the surface roughness is 0.75 μm at best (see Figure 9). The 3-D plot of Speed and Feed shows a much better relationship between the two factors. The lower speed (RPM) and the low and higher feed will give more room for the variation of the factors (see Figure 10). The 3-D plot of Speed and Hardness shows a greater effect on the outcome of the two variables. A slower RPM and a higher hardness will produce the most optimum surface finish (see Figure 11).

To further prove that RPM is the most significant factor, additional 20 replicates of 6061-Al blocks were milled at 2500 RPM. The hardness would be considered at the lowest level of the experiment with speed at mid-range. The average surface roughness reading of the 20 blocks was 0.92 μm. For 7075-Al, a total of additional 19 blocks were machined and the measurements were made in the same manner. Additional testing of 17 steel blocks, which was milled at 1500 RPM, produced an average surface roughness reading of 1.16 μm. Steel represents the highest level of hardness and the speed at mid-range. When compared to the 3-D generated chart of Figure 9, the data fall in the green range of acceptable surface finish. Of the three, the steel was a better fit. The experiment indicates that RPM for aluminum blocks could have been decreased and achieved a better surface finish. The steel would have performed better with a slower RPM. The additional measurement data are shown in Figures 12 and 17, representing four readings of surface roughness on each bore diameter along the +/- X and +/- Y directions. In this additional cutting, a single tool was used to cut each material. For the 65-mm bore of 6061-Al blocks, the surface roughness increases as cutting continues, which may have been associated with the tool wear. However, the 50-mm bore of 7075-Al cases, the readings are fairly constant. For steel blocks, the upward trend is more prominent, yet it may have been different if stronger tool bits were employed.

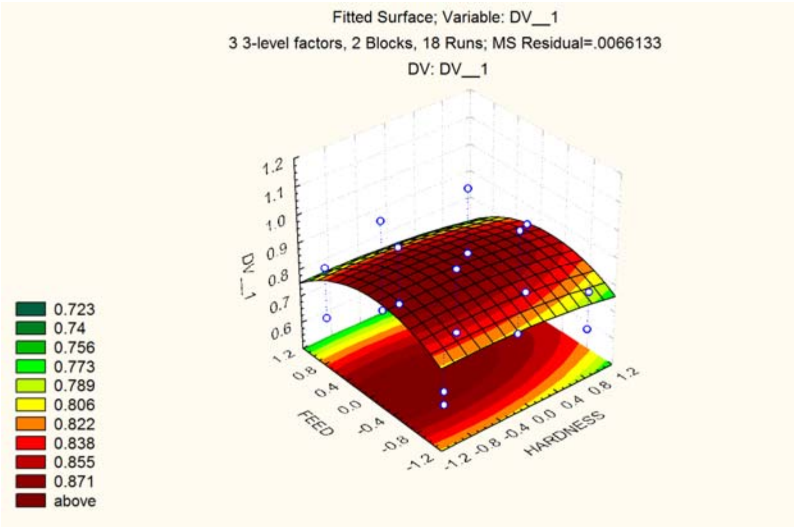

Figure 9. The 3-D plot of feed and hardness.

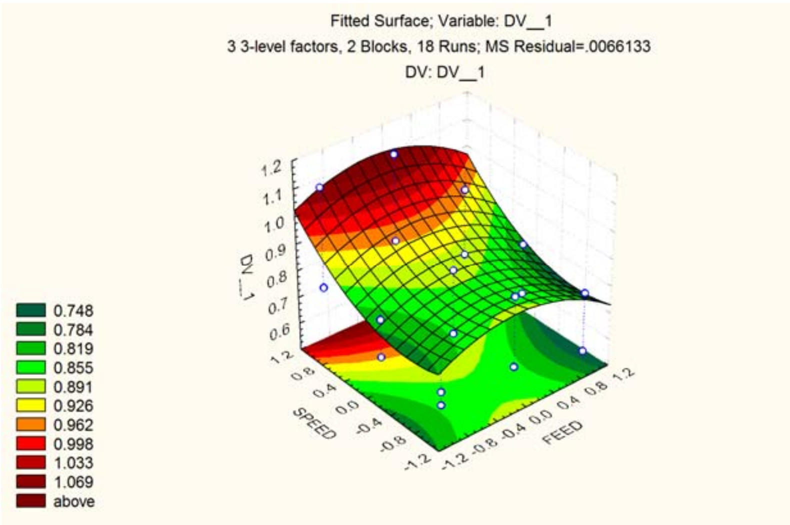

Figure 10. The 3-D plot of speed and feed

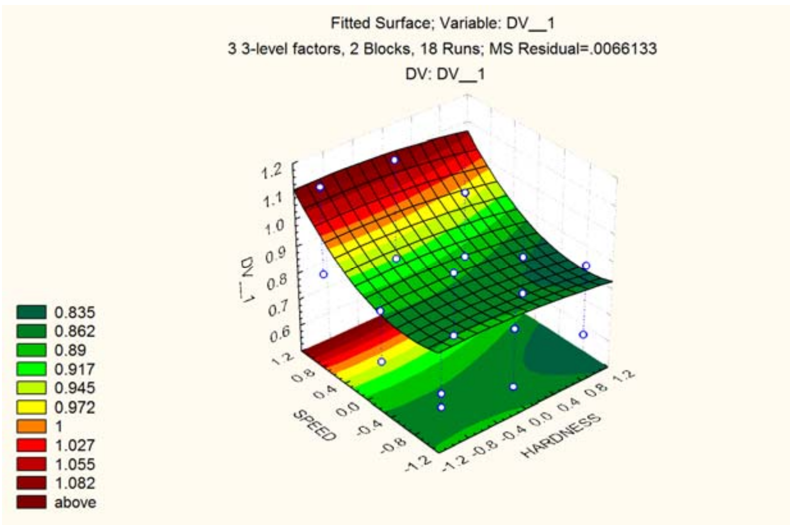

Figure 11. The 3-D plot of speed and hardness.

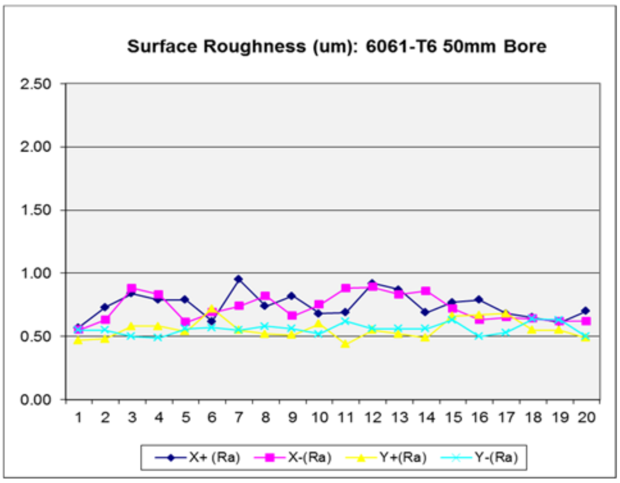

Figure 12. Surface roughness of 6061-Al blocks (50-mm bore).

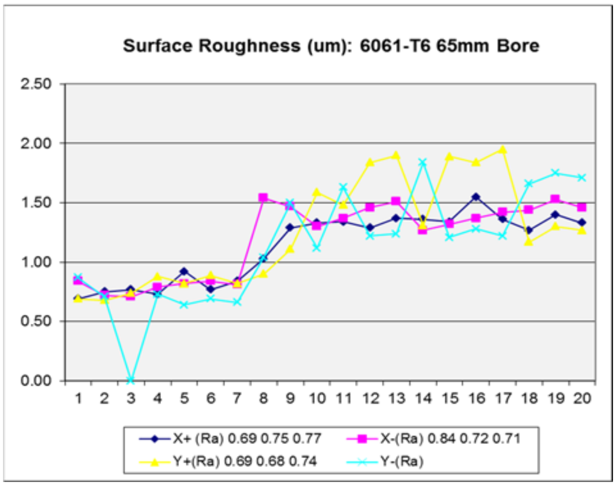

Figure 13. Surface roughness of 6061-Al blocks (65-mm bore).

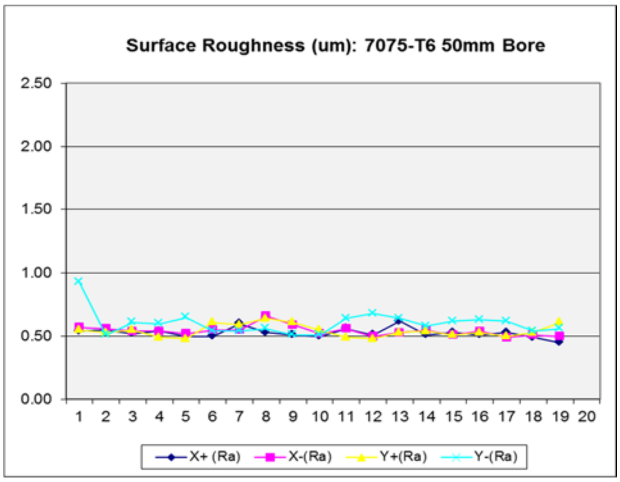

Figure 14. Surface roughness of 707-Al blocks (50-mm bore).

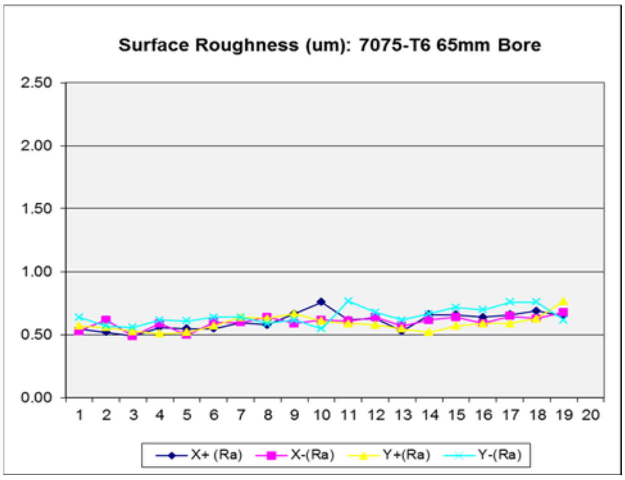

Figure 15. Surface roughness of 707-Al blocks (65-mm bore).

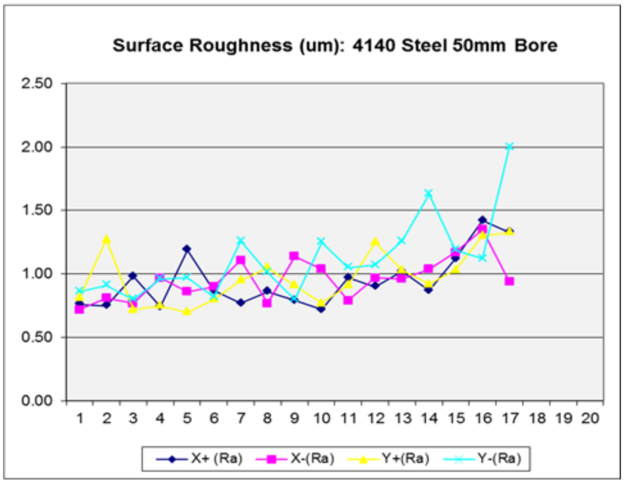

Figure 16. Surface roughness of 4140-Steel blocks (50-mm bore).

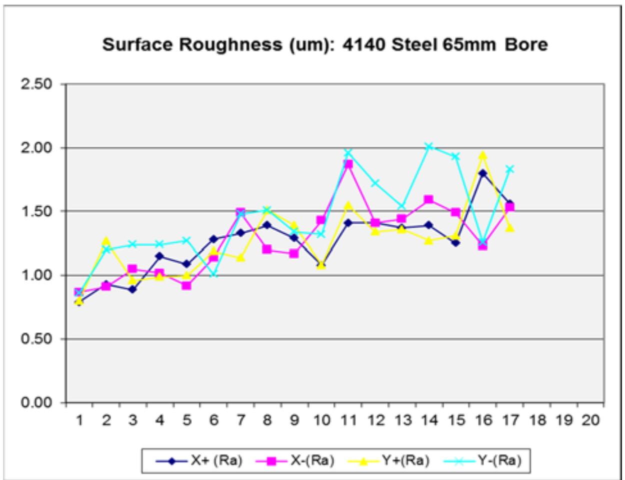

Figure 17. Surface roughness of 4140-Steel blocks (65-mm bore).

4. Conclusions

In this study, the most influential factors for the particular machine were found. The main effect was Hardness and the main interaction effect was Feed + Hardness. Therefore, the null hypothesis is rejected. Dimensional accuracy of the bore diameters was impacted by the significant factors. The experiments indicated that there is a difference between the CMM and probe measurements. Moreover, the Statistica software and ANOVA generation have identified the factor Speed to be the most significant factor for the surface roughness. Experience demonstrates that a slower feed rate and a high speed would create a better surface finish, which was validated using the single factor experiments. The three factor, three level experiment has shown that by varying the factors, a combination of different and possibly desirable surface finish can be achieved. The study on the CMM and probe diameter readings presented in this study is useful for today's manufacturing environment, by providing the optimum parameters for a variety of factors to achieve the acceptable quality levels.

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