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# Performance Assessment of Commercially Available CAD/CAM Software in the Manufacture of Sculptured Surfaces on a 3-Axis Vertical Machining Centre (VMC)

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***Abstract* — The efficiency with which sculptured surfaces are machined is dependent on the machining strategies used. The selection of machining parameters in commercially available CAD/CAM packages will in most cases depend on the choices provided in the software for the various machining strategies. The capabilities of commercially available CAD/CAM systems in relation to SSM will among other factors, be influenced by the computation times, cycle times as well as the resulting surface texture. The upgrading of CAD/CAM systems implies improvements in machining strategies and the attendant sculptured surface machining (SSM) efficiency. Therefore, instead of developing complex algorithms to improve the quality of machining, cycle times and surface texture, can be used to assess the quality of machining attainable in commercially available CAD/CAM systems if the performance on these parameters is acceptable. In this study, CAD/CAM designed free-form products were used to assess cycle times and surface quality of machined sculptured surfaces with NC-files generated by Mastercam® XIV and ArtCAM® 2013, respectively. The generated NC-files were fed into a 3-axis CNC Vertical Machining Center (VMC) for SSM. There was a significant difference in the resulting surface texture and cycle times between Mastercam® XIV and ArtCAM® 2013 machined free-form surfaces. This is a clear indication that different CAM systems (that is, Art-based, Mechanical-based and others) will yield different machining results even when similar machining strategies are employed. Mastercam® XIV performed better because of better curve approximations since, as a Mechanical-based CAM system, its development is focused on machining complex mechanical components.**

***Keywords — Sculptured surface machining (SSM); CNC machine tools; CAD/CAM systems, ArtCAM.***

## I. INTRODUCTION

A sculptured surface is a collection of small interconnected surface patches that maintain tangency (G1) or curvature (G2) continuity at the patch boundaries. Unlike surfaces for geometrical primitives (that is, planar and natural quadratic surfaces for cylinders, spheres and cones), sculptured surface normals vary from point to point on the surface patches [1, 2]. This makes it possible to design products with very complex geometries using free-form surfaces.

Modern engineering products are being designed with complex free-form surfaces for reasons that include design improvement, enhancement of functional requirements and aesthetic demands. For this reason, efficient machining of sculptured surfaces has become important in a number of manufacturing industries [3]. The automobile, aerospace, ship building and the die/mould making setups are some of the industries extensively using sculptured surfaces. In comparison with prismatic parts, free-form products tend to provide better ergonomic, aerodynamic and hydrodynamic functionality. The use of free-form surfaces in present-day engineering products is indeed growing rapidly, and as such, efficient machining of sculptured surfaces has become a noteworthy research area. The focus of sculptured surface machining (SSM) is to attain very complex free-form shapes with the highest quality and dimensional accuracy in the shortest time possible at minimal cost [4, 5].

Present-day advances in CAD/CAM technology have made it possible to manufacture very complex shapes [6]. The developments in CAD/CAM systems have also made virtual sculpting relatively easy, especially when using Art-based CAM packages. Before the advent of advanced computer systems, sculptured products were made with the help of skilled artists who were employed as pattern makers in manufacturing setups such as the foundry works [2]. Most of the currently available commercial CAM software cannot predict the surface finish. The surface generated during milling process is affected by different factors such as vibration, spindle run–out, temperature, tool geometry, feed, cross-feed, toolpath and other parameters [7]. This study focused on the effect of the G1 approximation of the CAD/CAM model of cycle time and surface finish. Improvements in virtual sculpting techniques, CAD/CAM software systems, cutting tool and machine tool technologies have resulted in the production of exceedingly high precision complex free-form parts in less cycle times [8]. Recent application packages such as ArtCAM® 2014, Solidworks® 2015, 3Ds max® 2015 and Mastercam® X8 have incorporated modelling approaches that allow production of complex free-form models with G1 and G2 continuity at surface boundaries with relative ease. Such models with the desirable boundary conditions at the surface seams make it a lot easier to generate the numerical control (NC) code required for computer numerical control (CNC) machining with minimal errors [2]. In practice, CNC part programs for free-form surfaces are generated exclusively with the help of CAM systems and whatever the machining strategy employed, the machined surface will always deviate from the ideal CAD/CAM model. This happens because the CAM systems generally convert the free-form surface into a polyhedron. As a result, the smooth design surface is approximated by a number of individual small planes [9, 10]. It is this polyhedron that is used to generate the NC-code and for collision detection. The NC part program lines (blocks) are usually short straight line trajectories of the form G1 X Y Z [11]. In the true sense, the machining result is no longer a free-form surface but a polyhedron. The part program (NC-code) controls the point to point movement of the tool and as such offering the capacity to machine virtually any form of surface, depending on the type of the machine tool used [9]. The positioning of the tool tip at the desired cutter location (CL) and guiding it along the specified path is achieved by automatic control of the motion of the CNC machine axes. Assuming all other design parameters are reasonably matching, the capacity of a CNC machine tool to machine highly complex shapes is mainly dependent on the number of axes (degrees of freedom) it has [12].

Machining parts with sculptured surfaces is very different from machining parts with regular surfaces. Regular or prismatic parts are generated in rather standard ways. This results in specific standard procedures being employed when machining prismatic shapes. There is a lot of freedom in designing free-form surfaces, and it is very difficult to classify morphological features made of sculptured surfaces into clearly defined categories as is the case with regular surfaces. This presents a lot of challenges in coming up with specific machining strategies and tools associated with them. Furthermore, morphological features made of sculptured surfaces are often machined in combination, whilst those with regular surfaces are normally machined individually [8]. This leads to relatively few cutting tools when machining sculptured surfaces compared to regular surface parts. The free-form surfaces are often machined on 3-axis CNC machine tools using the high-speed ball-end mill. The ball-end mill is the widely used tool in sculptured surface machining (SSM) because it is easy to position on 3-axis machines and does not need complicated cutter compensation [6, 8]. This approach enables the tool to take any position in the machining space of a given machine tool. On these machines, a contour is machined line by line by moving the three axes. The tool cannot be set at an angle as the 3-axis machine has no provision to rotate the axes. This limitation in the machine tool reduces the cutter accessibility [9]. The operator is, therefore, left with a tough decision on how best the free-form surface should be oriented in the CAM system before generating the NC code as well as during the actual machining process. Despite the limited degrees of freedom on a 3-axis machine, the kinematic design makes it much more rigid a machine tool, capable of handling relatively larger cutting forces and also limits chatter in the machining process compared to a 5-axis machine tool [9]. The machining accuracy is high enough to meet the finishing requirements of a good number of engineering applications. Above all, 3-axis CNC machine tools are generally cheaper and the cost of maintenance is relatively affordable even for small industrial setups [2].

In 2012, [13] compared the quality of the machined free-form products using PowerMill® and ArtCAM® pro, which are both Delcam products. They indicated that machining sculptured surfaces does not necessarily require a powerful CAM system but the choice of the CAM system will depend on the complexity of the product. They concluded that the difference between PowerMill® and ArtCAM® machined sculptured products is not recognizable [13]. They, however, did not show the precise difference in surface texture with measurements of surface roughness. Besides, the CAM packages used were from the same vendor and as such, the quality of the machined free-form products could only show minimal differences in surface texture [13]. In a related study, [14] used SolidCAM® to design a free-form surface and later machined it on a 3-axis CNC machine tool, with the aim of determining the appropriate procedure for selecting the tool path strategy when machining sculptured surfaces. This work employed Solidworks® 2013 to sculpt the free-form surfaces for surface quality assessment, and two CAM packages from two different vendors were used to machine the sculptured surfaces [15].

The CAM generated tool motions comprise a series of short linear trajectories of the form G1 X Y Z. At the end of each one of these blocks, the tool motions are allowed to cease. The resulting acceleration and velocity changes at the block seams are undesirable as they increase machine tool vibrations and the cycle time (Table I). In an effort to reduce these effects and improve cycle times, CAM systems employ smoothing algorithms, and much more recent packages compress the linear trajectories into splines. The linear interpolation trajectories (G1) should not be forgotten, as they keep providing good results, combined with the smoothing features of the CAM system [9, 16]. Despite the smoothing approaches used to minimise velocity and acceleration jerking in between NC blocks, there is still some degree of cycle time increase due to this effect. In the absence of the knowledge to develop complex algorithms to improve the quality of machining, existing CAM systems may be used to come up with machining parameters that will yield relatively efficient machining results [12, 15]. In this study, sculptured surfaces were machined on a 3-axis CNC machine tool, using machining strategies contained in the CAM systems, in a single setup and then assessed the quality of the resulting surfaces [15]. The following were the specific objectives:

i. To design sculptured products using Solidworks® 2013 and then export them into ArtCAM® and Mastercam® for subsequent processes,
ii. To determine the appropriate toolpath planning within the respective CAM system and generate the G-code for subsequent machining of the designed sculptured products on a 3-axis vertical machining centre (VMC) in a single setup,
iii. To compare the ArtCAM® and Mastercam® predicted cycle times with the actual machining times on the 3-axis vertical machining centre (VMC), and
iv. To assess the quality of the surface finish of the machined free-form surfaces whose G-code was generated using Mastercam® XIV and ArtCAM® 2013®.

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## II. METHODOLOGY

*General Method*

The general method involved modelling sculptured products and subsequently machining the products on the Supermax 65A 3-axis (VMC). The cycle times for the machined free-form surfaces were noted. The sculptured products were then analyzed for surface quality using the Hobson Talysurf surface finish analyser. The following is the generalisation of the procedure that was followed:

i. Creating a 3D Model using Solidworks® 2013®,
ii. Selecting a cutting strategy and conditions for part roughing in both Mastercam® XIV or ArtCAM® 2013®,
iii. Roughing simulation using the respective CAM Package,
iv. Generation of G-code for part roughing,
v. Selection of the cutting strategy and conditions for part finishing,
vi. Finishing simulation in the respective CAM Package,
vii. Generation of G-code for part finishing,
viii. Part machining with possible dimensional accuracy and part surface quality errors,
ix. Assessment of the cycle times for the machined sculptured products, and
x. Assessment of surface quality for the machined free-form products.

*Specific Procedure*

Four 20x12x10 mm Aluminium blocks were used as workpieces (WPC) for machining the free-form faces with G-code generated from both ArtCAM 2013® and Mastercam XIV®. Fig. 1 shows one of the workpieces after roughing and the final ball-nose finishing. The toolpaths were generated with a machining angle of $45^0$ , the cutting method was zigzag and a specified tolerance of 0.005 for both Mastercam XIV® and ArtCAM 2013®. An 8 mm diameter Flat End Mill was used for roughing, followed by the 5 mm ball-nose finishing. Five centre line average (CLA) measurements were made for each of the four sculptured surfaces using the Talysurf 4 surface texture measurement equipment for both ArtCAM® and Mastercam® machined free-form surfaces. Table III shows the surface texture results. Fig. 2 is the graph of surface roughness in microns against the feedrate for the Mastercam® (CLA M) and ArtCAM® (CLA A) machined sculptured surfaces.

Fig. 1. Free-form surface after ball-nose finishing.

## III. RESULTS

The actual cycle times for both surface roughing and finishing were longer than the CAM predicted cycle times as shown in Table I. Most of the machining time in SSM were taken up by the ball-nose finishing. Fig. 3 shows the cycle time difference for the ball-nose finishing. Comparing the actual cycle times for surface finishing, it is observed that it takes slightly longer to machine with Mastercam®. This difference is despite using similar machining strategies for both CAM systems.

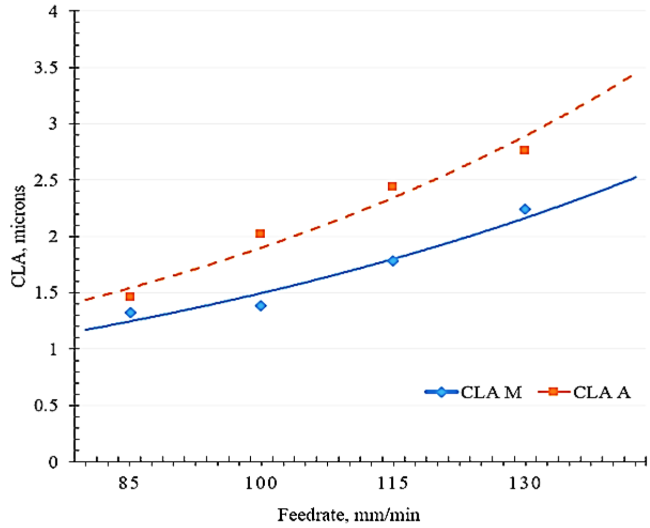


Fig. 2. Plot of surface roughness for Mastercam® (CLA M) and ArtCAM® (CLA A) machined surfaces against feedrate.

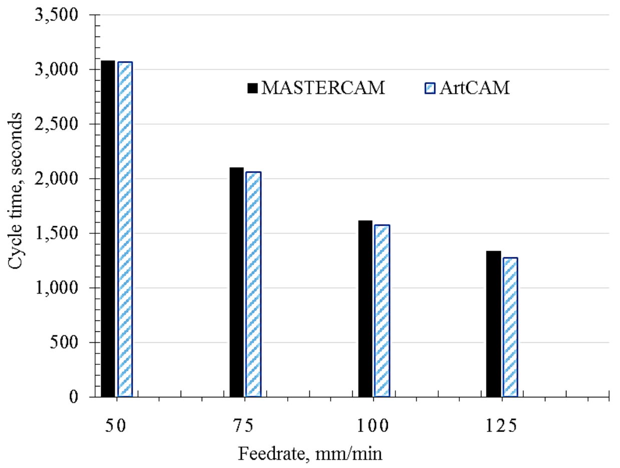


Fig. 3. Comparison of cycle times for Mastercam® XIV with ArtCAM® 2013 against feedrate.

The surface quality results shown in fig. 2 indicate that Mastercam XIV® gives a better surface finish than ArtCAM 2013®. This is an indication that the linear (G01) approximation of the spline generate free-form surface is much more accurate with Mastercam XIV® than ArtCAM 2013®. Thus, when machining sculptured surface products requiring tighter tolerances, Mastercam® would be a better choice [15]. Tables I and II show the machining parameters which were used in this study.

TABLE I. PARAMETERS AND RESULTS FOR SURFACE FINISHING USING MASTERCAM XIV®

| WPC | Machining strategy | Feedrate [mm/min] | Plunge rate [mm/min] | Spindle speed [rpm] | Retract rate [mm/min] | Stepover [mm] | CAM cycle time [s] | Actual cycle time [s] | Cycle time difference [s] |
|---|---|---|---|---|---|---|---|---|---|
| A | Surface finish parallel | 50.00 | 20.00 | 650.00 | 15.00 | 0.10 | 2,985.02 | 3,079.00 | 93.98 |
| B | Surface finish parallel | 75.00 | 25.00 | 700.00 | 15.00 | 0.10 | 1,997.14 | 2,102.00 | 104.86 |
| C | Surface finish parallel | 100.00 | 25.00 | 725.00 | 15.00 | 0.10 | 1,508.46 | 1,620.00 | 111.54 |
| D | Surface finish parallel | 125.00 | 25.00 | 750.00 | 15.00 | 0.10 | 1,215.24 | 1,338.00 | 122.76 |

TABLE II. PARAMETERS AND RESULTS FOR SURFACE FINISHING USING ARTCAM 2013®

| WPC | Machining strategy | Feedrate [mm/min] | Plunge rate [mm/min] | Spindle speed [rpm] | Stepover [mm] | Stepdown [mm] | Actual cycle time [s] |
|---|---|---|---|---|---|---|---|
| R | Relief finish toolpath | 50.00 | 20.00 | 650.00 | 0.10 | 1.00 | 3,065.00 |
| S | Relief finish toolpath | 75.00 | 25.00 | 700.00 | 0.10 | 2.00 | 2,056.00 |
| T | Relief finish toolpath | 100.00 | 25.00 | 725.00 | 0.10 | 2.50 | 1,575.00 |
| U | Relief finish toolpath | 125.00 | 25.00 | 750.00 | 0.10 | 3.00 | 1,275.00 |

The surface roughness results obtained using the Talysurf 4 surface texture equipment are given in Tables III and IV. They clearly show the difference in surface quality for the ArtCAM® and Mastercam® machined surfaces.

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TABLE III. SURFACE TEXTURE MEASUREMENTS FOR MASTERCAM® MACHINED FREE-FORM PROFILES

| WPC | Feedrate [mm/min] | CLA readings | | | | | | CLA [microns] |
|---|---|---|---|---|---|---|---|---|
| | | *Sample* | *1* | *2* | *3* | *4* | *5* | |
| A2 | 85 | Measurement | 0.014 | 0.012 | 0.11 | 0.015 | 0.14 | 1.32 |
| | | Scale factor | 100 | 100 | 10 | 100 | 10 | |
| | | Result | 1.4 | 1.2 | 1.1 | 1.5 | 1.4 | |
| B2 | 100 | Measurement | 0.01 | 0.13 | 0.017 | 0.018 | 0.11 | 1.38 |
| | | Scale factor | 100 | 10 | 100 | 100 | 10 | |
| | | Result | 1 | 1.3 | 1.7 | 1.8 | 1.1 | |
| C2 | 115 | Measurement | 0.12 | 0.11 | 0.02 | 0.016 | 0.03 | 1.78 |
| | | Scale factor | 10 | 10 | 100 | 100 | 100 | |
| | | Result | 1.2 | 1.1 | 2 | 1.6 | 3 | |
| D2 | 130 | Measurement | 0.024 | 0.025 | 0.02 | 0.02 | 0.023 | 2.24 |
| | | Scale factor | 100 | 100 | 100 | 100 | 100 | |
| | | Result | 2.4 | 2.5 | 2 | 2 | 2.3 | |

TABLE IV. SURFACE TEXTURE MEASUREMENTS FOR ARTCAM® MACHINED FREE-FORM PROFILES

| WPC | Feedrate [mm/min] | CLA readings | | | | | | CLA [microns] |
|---|---|---|---|---|---|---|---|---|
| | | *Sample* | *1* | *2* | *3* | *4* | *5* | |
| R2 | 85 | Measurement | 0.012 | 0.12 | 0.019 | 0.014 | 0.016 | 1.46 |
| | | Scale factor | 100 | 10 | 100 | 100 | 100 | |
| | | Result | 1.2 | 1.2 | 1.9 | 1.4 | 1.6 | |
| S2 | 100 | Measurement | 0.012 | 0.025 | 0.026 | 0.018 | 0.02 | 2.02 |
| | | Scale factor | 100 | 100 | 100 | 100 | 100 | |
| | | Result | 1.2 | 2.5 | 2.6 | 1.8 | 2 | |
| T2 | 115 | Measurement | 0.019 | 0.022 | 0.021 | 0.031 | 0.029 | 2.44 |
| | | Scale factor | 100 | 100 | 100 | 100 | 100 | |
| | | Result | 1.9 | 2.2 | 2.1 | 3.1 | 2.9 | |
| U2 | 130 | Measurement | 0.29 | 0.026 | 0.22 | 0.035 | 0.026 | 2.76 |
| | | Scale factor | 10 | 100 | 10 | 100 | 100 | |
| | | Result | 2.9 | 2.6 | 2.2 | 3.5 | 2.6 | |

## IV. CONCLUSION

An iterative toolpath planning approach employed in this study shows that similar machining strategies produce different machining results. The machining strategy affects the total machining time and the surface quality. The difference between the actual and the CAM predicted cycle times was a clear indication of the effects of acceleration and velocity jerks in between part program lines [9, 16]. The G1 approximation of the spline generated surfaces does not only affect the cycle time but also the quality of machining. The ArtCAM® and Mastercam® generated G-code yield different machining results even when similar machining strategies are used. The difference in surface roughness between Mastercam® XIV and ArtCAM® 2013 machining results (fig. 3) shows the difference in the quality of machining. Thus, the quality of machining attainable in any given commercially available CAM system can be deduced from cycle times as well as the surface texture of the machined sculptured surfaces [15]. Most developing countries are facing economic challenges and have limited skills levels to develop complex algorithms to improve the quality of machining sculptured products. For this reason, research work like this one and a lot more, such as the ones carried out earlier by Mwanza and Malama [17–20] on the Supermax 65A VMC would be of great benefit to developing countries.

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