Fixturing error measurement and analysis using CMMs

To cite this article: Y Wang et al 2005 J. Phys.: Conf. Ser. 13 163

View the article online for updates and enhancements.
Fixturing error measurement and analysis using CMMs

Y Wang, X Chen and N Gindy
School of Mechanical, Materials and Manufacturing Engineering,
The University of Nottingham, Nottingham NG7 2RD, UK.

Abstract. Influence of fixture on the errors of a machined surface can be very significant. The machined surface errors generated during machining can be measured by using a coordinate measurement machine (CMM) through the displacements of three coordinate systems on a fixture-workpiece pair in relation to the deviation of the machined surface. The surface errors consist of the component movement, component twist, deviation between actual machined surface and defined tool path. A turbine blade fixture for grinding operation is used for case study.

1. Introduction
Error measurement and analysis is indispensable for fixture evaluation, because (a) the machined component quality can be judged against its accuracy requirement; (b) the error analysis may provide the reasons of component non-conformity and the suggestions of quality improvement; (c) verification of theoretical assumptions in the design. Error analysis and measurement is often conducted via investigation of deviation between nominal machined surface and actual machined surface, which is defined as the machined surface error.

Most researches on machined surface error focused on errors from cutting tool such as cutting force, cutter deflection, cutter wear etc. [1~3]. When fixturing errors were taken into account, locating error was often regarded as the solo source of the surface error [4~5]. In fact, apart from locating error, component movement and deformation can be significant to the machined surface error. Component may move during machining due to insufficient fixture constraint or inadequate fixture layout. Component may deform as a result of fixturing and machining. The machined surface may be sprung back from the tool path once deformation is relaxed. The amount of the spring back depends on the position and orientation of the machined surface in relation to fixturing positions and machining parameters.

There are three types of facilities for measuring machined surface error: Dial Test Indicators (DTIs), displacement sensors and Coordinate Measurement Machines (CMMs). A DTI or displacement sensor can only measure the displacement of a particular point of component in a defined direction. Since an object in space has six degrees of freedom, six sensors or DTIs are required to determine the displacement of component in relation to fixture and machine [6]. For a complete measurement of component displacement, such as component distortion or twist measurement, twelve sensors or DTIs may be required. The measurement with such large number of sensors or DTIs is a tedious and unrealistic job for industry. A CMM may offer a good solution for decomposing fixturing error sources by measuring the displacement of the coordinate systems on the component and the fixture. This paper presents a method of fixturing error measurement including component movement and component deflection.
2. Measurement methodology

Three coordinate systems (CSs) may be involved in a CMM measurement for fixturing error analysis. As shown in figure 1, CSf is the CS on the fixture, CSm is the CS on the machined side of the workpiece, and CSum is the CS on the un-machined side of the workpiece. The method to measure the displacements of these three coordinate systems using CMM was introduced in [7]. These three CSs are measured before and after machining. The assumptions applied to the measurement are: (a) there is no deformation on the un-machined side of the workpieces; (b) the fixture has good positional repeatability with respect to the machine, so that the machining tool path could be represented by CSf as a reference. Therefore the machined surface error can be defined as the maximum positional difference from nominal machined surface to actual machined surface in the direction of interest. Here Sm, Sum and Sf are used to represent the nominal machined surfaces in relation to the coordinate systems CSm, CSum and CSf respectively; and Sa denotes the actual machined surface. Since the fixture has good repeatability, Sf can be used to represent the tool path.

Since there is no deformation on the un-machined side of workpiece, the position difference of CSum with respect to CSf generated from machining should be resulted from the workpiece movement. As indicated in figure 1(a), the bold solid line is the tool path Sf, and the movement of the workpiece makes the nominal machined surface Sf move to Sum, shown as a bold dashed line. As shown in figure 1(b), with respect to CSum, the nominal machined surface is Sum, and the actual machined surface is Sf. Therefore, the surface error caused by the workpiece movement \( E_{mv} \) is the position difference from Sum to Sf.

![Figure 1](image1.png)

Figure 1. The surface error caused by the workpiece movement.

![Figure 2](image2.png)

Figure 2. The surface error caused by workpiece deformation.

In figure 2(a), the workpiece may be bended during the fixturing and machining process. The position of CSm might be different with regard to CSum before machining and after machining. Therefore, surface Sm may not be aligned with surface Sum. As shown in figure 2(b), Sm (Dash bold line) is the nominal machined surface with respect to CSm. Sum (Solid bold line) is the actual machined surface, the effect of workpiece twist \( E_{wt} \) is expressed by the deviation of Sm from Sum. As shown in figure 3, the position difference \( E_{fa} \) of tool path Sf during machining (Bold Dashed line) and the actual machined position Sa (Solid bold line) after machining deformation is released.

As illustrated in figure 4, the resultant surface error generated during machining \( E_m \) is:

\[
E_m = E_{mv} + E_{wt} + E_{fa} = (Sf - Sum) + (Sum - Sm) + (Sa - Sf) = Sa - Sm \]  

(1)
Namely, the resultant surface error generated from machining process should be the position difference between the actual machined surface position and the nominal machined surface position.

3. Case study
A turbine blade fixture for grinding is used as an example as shown in Figure 5. Four points on the ground surface were measured from four ground samples. Therefore, total 16 sample points were measured in the experiment. Before grinding, since there was no grinding error, $S_{um}$ and $S_m$ were coincident with $S_f$. Therefore, $S_{um}$ and $S_m$ are the expressions of $S_f$ using $CS_m$ and $CS_{um}$ as references respectively. After grinding, even though the expressions of $S_f$, $S_m$ and $S_{um}$ were still the same using $CS_m$, $CS_{um}$ and $CS_f$ as references respectively, they were not coincident with each other any more due to the grinding error. In order to calculate the grinding error, it is more convenient to express the surfaces using a common reference. Therefore, $CS_{um}$ and $CS_m$ after grinding were expressed regarding to $CS_f$. $S_a$ is measured directly after grinding using $CS_f$ as reference. The position differences between $S_{um}$, $S_m$, $S_f$ and $S_a$ after grinding in response to $CS_f$ were calculated.

The displacements of the four vertex points P1 ~ P4 on the direction normal to the machined surface generated during rough grinding are shown in table 1. The direction away from the machined surface is positive. The machined surface errors arising from component movement, component deformation, the deviation between tool path to actual machined surface and the resultant machined surface errors generated during fixturing and grinding are shown in table 2.

4. Conclusive remarks
The machined surface error induced by fixturing is the resultant error of locating error, component movement, component deformation, tool path variation during fixturing and machining process. The resultant machined surface error can be measured based on the displacement of the three coordinate systems: one on fixture, one on the machined side of component and one on the un-machined side of
component. The deviation of machined surface can be interpreted as the displacements of these coordinate systems. The case study of the turbine blade fixture indicated that the deviation between actual machined surface and tool path is the major error source of the machined surface error generated during machining.

Table 1. Surface error generated during rough grinding

|                | Surface error on the contour points |
|----------------|-----------------------------------|
|                | $\Delta P_1$ (mm) | $\Delta P_2$ (mm) | $\Delta P_3$ (mm) | $\Delta P_4$ (mm) | Absolute max error (mm) |
| Blade movement | Ave | 0.053 | 0.053 | -0.002 | -0.013 | 0.053 |
|                | Range | 0.031 | 0.028 | 0.033 | 0.030 | 0.033 |
|                | STDDEV | 0.015 | 0.013 | 0.015 | 0.014 | 0.015 |
|                | Ave | 0.013 | 0.051 | 0.023 | 0.063 | 0.063 |
|                | Range | 0.024 | 0.033 | 0.027 | 0.041 | 0.041 |
|                | STDDEV | 0.011 | 0.015 | 0.013 | 0.018 | 0.018 |
| Blade twist   | Ave | 0.639 | 0.590 | 0.296 | 0.184 | 0.639 |
|                | Range | 0.164 | 0.276 | 0.318 | 0.260 | 0.318 |
|                | STDDEV | 0.071 | 0.115 | 0.137 | 0.109 | 0.137 |

Table 2. Surface error decomposition

|                | $E_{mv}$ | $E_{wt}$ | $E_{mE}$ | $E_m$ |
|----------------|---------|---------|---------|------|
| Surface error  | 0.053mm | 0.063mm | 0.639mm | 0.755 mm |

Acknowledgement
The authors gratefully acknowledge the technical and financial support from Rolls-Royce plc.

References
[1] Kline W A, DeVor R E and Shareef I A 1982 “The prediction of surface accuracy in end milling”, Transaction of the ASME, Journal of Engineering for Industry 104 (1982)272-278.
[2] Sutherland J W and DeVor R E 1986 “An improved method for cutting force and surface error prediction in flexible end milling systems”, Transaction of the ASME, Journal of Engineering for Industry 108(1986) 269-279.
[3] Yun W and Ko J H et al. 2002 “Development of a virtual machining system, part2: prediction and analysis of a machined surface error”, International Journal of Machine Tool & Manufacture 42(2002) 1607-1615.
[4] Rong Y, Hu W, Kang Y, Zhang Y and Yen D W 2001 “Locating error analysis and tolerance assignment for computer-aided fixture design”, International Journal of Production Research, 39(2001), 3529-3545.
[5] Marin R A and Ferreira P M “Analysis of the influence of fixture locator errors on the compliance of work part features to geometric tolerance specifications”, Journal of Manufacturing Science and Engineering, Transaction of ASME.
[6] DeMeter E C and Hockenberger M J 1997 “ The application of tool path compensation for the reduction of clamping induced geometric errors”, International Journal of Production Research, 35(12) (1997) 3415-3432.
[7] Wang Y and Chen X et al. 2003 “Fixture evaluation based on CMM”, Laser Metrology and Machine Performance VI, Wit press, 2003, p 231-241.