Fixturing error measurement and analysis using CMMs

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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, CS$_f$ is the CS on the fixture, CS$_m$ is the CS on the machined side of the workpiece, and CS$_{um}$ 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 CS$_f$ 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 $S_m$, $S_{um}$ and $S_f$ are used to represent the nominal machined surfaces in relation to the coordinate systems CS$_m$, CS$_{um}$ and CS$_f$ respectively; and $S_a$ denotes the actual machined surface. Since the fixture has good repeatability, $S_f$ can be used to represent the tool path.

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

In figure 2(a), the workpiece may be bended during the fixturing and machining process. The position of CS$_m$ might be different with regard to CS$_{um}$ before machining and after machining. Therefore, surface $S_m$ may not be aligned with surface $S_{um}$. As shown in figure 2(b), $S_m$ (Dash bold line) is the nominal machined surface with respect to CS$_m$. $S_{um}$ (Solid bold line) is the actual machined surface, the effect of workpiece twist $E_{mt}^m$ is expressed by the deviation of $S_m$ from $S_{um}$. As shown in figure 3, the position difference $E_{fa}^m$ of tool path $S_f$ during machining (Bold Dashed line) and the actual machined position $S_a$ (Solid bold line) after machining deformation is released.

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

$$E_m = E_{mv}^m + E_{mt}^m + E_{fa}^m = (S_f - S_{um}) + (S_{um} - S_m) + (S_a - S_f) = S_a - S_m$$ (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

| Blade movement | Surface error on the contour points |
|----------------|------------------------------------|
| Ave | ΔP₁ (mm) | ΔP₂ (mm) | ΔP₃ (mm) | ΔP₄ (mm) | Absolute max error (mm) |
| 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 |
| Blade twist | Ave | ΔP₁ (mm) | ΔP₂ (mm) | ΔP₃ (mm) | ΔP₄ (mm) | Absolute max error (mm) |
| 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 |
| faEₘ | Ave | ΔP₁ (mm) | ΔP₂ (mm) | ΔP₃ (mm) | ΔP₄ (mm) | Absolute max error (mm) |
| 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

| Surface error | Eₘₑ | Eₘᵢ | Eₘₑ | Eₘₑ |
|---------------|------|------|------|------|
| Ave | 0.053mm | 0.063mm | 0.639mm | 0.755 mm |

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