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Increasing the workpiece precision through volumetric compensation of the milling machine geometry

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Abstract
Today's technical products consist of components with constantly increasing demands for precision. Finest as well as large structures must be manufactured very precisely for various applications. The most frequently used machining process for this is milling. To meet these accuracy requirements high precision machine tools and perfect climate conditions are required, causing increased manufacturing costs. An upcoming method for increased precision in milling is the volumetric compensation of the machine geometry. Various measurements show an increase in machine tool accuracy with this method for unloaded axis movements. The method has been proven to reduce axis errors by 50 - 90 %. Evidence that this improvement is also fulfilled on the workpiece is still missing.
In this study, the achieved tolerance of test workpieces made of aluminium alloy with a milling machine in the original and in the volumetrically compensated condition are investigated and compared. For the experimental tests, a workpiece design with relevant geometrical characteristics such as holes and circular pockets as well as squares and hexagons parallel to the axis and not parallel to the axis is machined. For the evaluation, the axis deviations and the machined workpiece deviations are analysed for both conditions showing an improvement of 50 % through volumetric compensation. In addition, the perpendicularity and parallelism of the machine axes prove a significant improvement in workpiece tolerances. For the circular pockets, there is both a considerable improvement in position and an increase in circularity from IT3 to IT1. As a result, a high improvement in workpiece accuracy is achievable with volumetric compensation. The limiting factor of precision improvement with the method presented is the machine tool repeatability.

Milling Machine, Machine Precision, Volumetric Compensation, Workpiece Precision

1. Introduction

Volumetric compensation has established itself as a method for increasing the accuracy of machine tools and machining centres. Originally developed for the calibration of coordinate measuring machines, volumetric compensation is used for high-precision machine tools to an increasing extent. Independent measurements in the static state show a reduction of straightness, squareness and axis rotation errors after compensation of 50 - 90 % [1, 2, 4]. However, the results in the static state do not allow a conclusion about the part accuracy, since the dynamic and thermal behaviour of the machine tool are only taken into account to a limited extent. Evidence of the impact of compensation on the workpiece quality is to be provided by this study through the machining of workpieces.

2. Experimental design

In order to demonstrate the influence of a volumetrically compensated milling machine geometry on the workpiece accuracy, the primary objective is to carry out a series of tests under constant conditions. The volumetric machine errors are measured with a laser tracer based on the measuring principle of multilateration [2, 3]. The steps of the measurement are between 12.5 mm and 17 mm, depending on the axis. The mechanical axis deviations are within the tolerance specified by ISO10791 (straightness 10 µm, squareness 40 µrad). The reversal range in all directions is ± 3 µm. The error compensation is done by a calculated compensation table with 10 mm steps linear interpolated according to Schwenke et al. [2]. Based on the compensation table embedded in the machine control, the machine can add the reverse error vector to the axes positions.

In this work, two workpieces of the same geometry are milled, containing circular pockets, squares, a hexagon and holes (Fig. 1). One workpiece represents the uncompensated machine status while the second is milled with the same machine tool in a compensated status. The aluminium alloy EN AW 5083 from one batch is used as raw material. Clamping on the machine is carried out in the same range of less than 0.02 mm in Y- and Z-direction and less than 1 mm in X-direction with defined force by clamping claws.

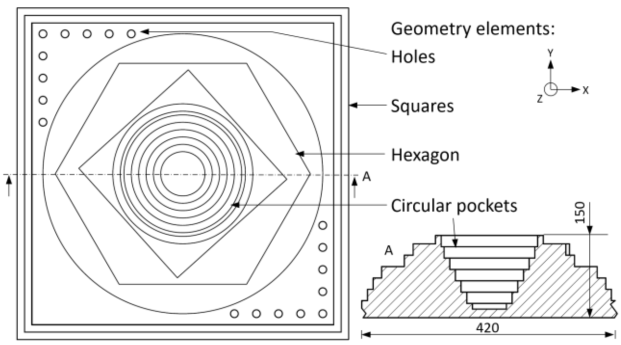

Figure 1. Test workpiece with representative geometries

A thermally comparable condition is achieved by a hot run cycle according to ISO 230 specified by the machine manufacturer. The ambient temperature was 20°C ± 0.5 °C and the machine tool and measuring equipment were not exposed to solar radiation. After machining, the two workpieces are measured on a high-precision coordinate measuring machine (E_0 = 1.2 + L/350 µm) recently approved according to ISO 10360.

3. Improvement for circular shapes

The position of the circular pockets is evaluated with reference to the first circular pocket with 80 mm diameter. In the uncompensated setting, the position deviation is up to 0.01 mm (Fig. 2). In comparison, volumetric compensation reduces the position deviation to ± 2 µm, reflecting the repeatability of the machine tool.

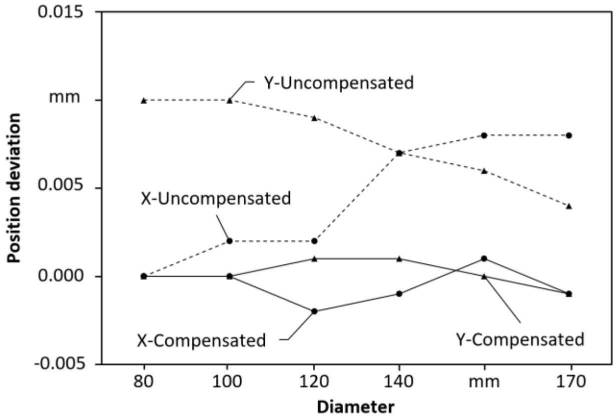

Figure 2. Position deviation of circular pockets

Next to the position deviation, the roundness error of the circular pockets has been analysed. A significant improvement in roundness is observed for all diameters investigated (Fig. 3).

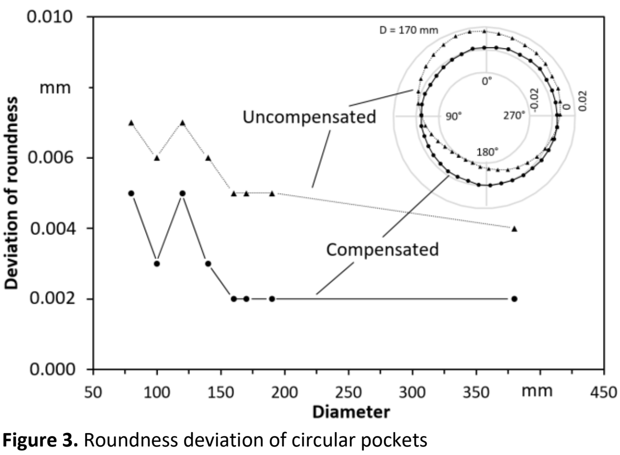

Figure 3. Roundness deviation of circular pockets

Similar to the position deviation, the compensation capability is limited by the precision of reproducibility of the machine tool. Comparing the roundness deviations with the basic tolerance series, an improvement from IT3 to IT1 is achieved. The average reduction of deviations for all measured round geometries (n = 8) reaches 34 %.

4. Improvement for straight geometries

The straightness deviations are measured along steps of the squares. Straight geometries along the X-axis have smaller deviation in the Y- as well as in the Z-direction compared to straight geometries along the Y-axis. The highest error reduction by volumetric compensation is observed in the deviation in Y-direction (ΔY) when moving the X-axis. For illustration, Fig. 4 shows the machine error EYX (Error in Y-direction moving the X-axis) for the uncompensated and the compensated machine tool in comparison with the measured deviations for straight geometries on the workpiece (ΔY).

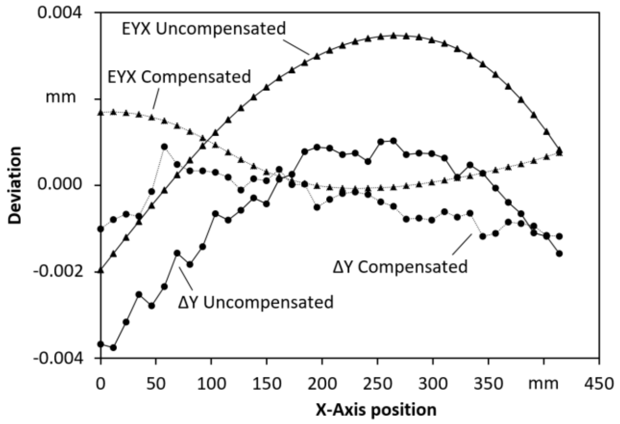

Figure 4. Comparison between machine deviation EYX and the straightness deviation on the workpiece

The measurement data demonstrate that an axis deviation measured in the unloaded machine tool (EYX) is transferred to the workpiece (ΔY) in the same way. Similar to the data for circular geometries the deviation with the volumetric compensation is reduced to the range of machine repeatability. For this reason, the graphs for the compensated machine do not show a uniform progression. Overall, volumetric compensation improves the straightness of the machined steps by an average of 25%.

5. Summary and Conclusion

This study investigate workpiece accuracy gains from volumetric compensation for representative geometries in mechanical engineering. The position and shape deviation of squares, holes, hexagons and circular pockets were analysed.

A reduction in deviations was observed across the board. Smaller features tend to show less influence of the machine geometry, as shown by the roundness deviations of the circular pockets in the centre of the part. In summary, the compensated machine tool achieves an accuracy of ± 2 µm, as illustrated by the straightness of the milled steps. An improvement of 33 % on average was achieved in the position deviations. No further improvement could be observed for shape and position features, which already achieve a deviation of less than ± 2 µm.

In conclusion, the increase in machine accuracy by volumetric compensation in the unloaded static state also leads to an improvement in the workpiece accuracy to the same extent.

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