Volumetric Accuracy of Machine Tools for Five-Axis Machining

The World Champion of Precision

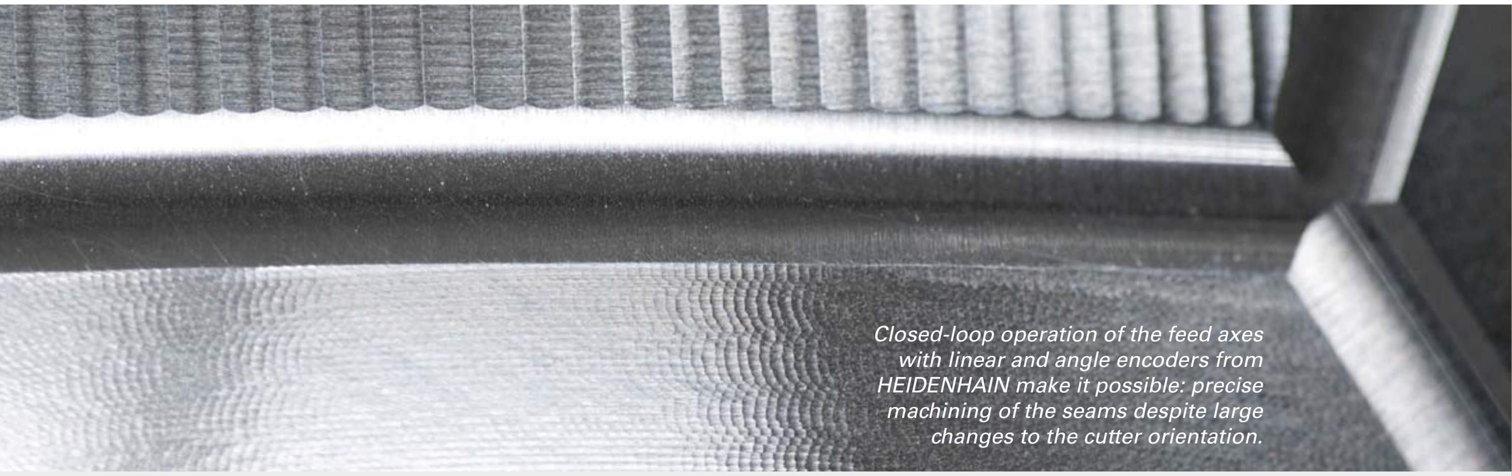
For numerous machining tasks, five-axis machining offers obvious economic advantages compared with standard three-axis machining. However, distinctly more complex feed movements must be taken into account in order to reduce the machining times and the number of rechucking operations. Depending on the axis arrangement and fixture situation, considerably longer traverse paths in the linear and rotatory feed axes can result, even during the machining of small workpieces. Since the deviations between the ideal motion and the actual behavior of a feed axis usually increase as the traverse path becomes longer, machine tools for five-axis machining are presented with a special challenge: the manufacture of precise workpieces is only possible with a sufficiently high volumetric accuracy of the machine tool.

In contrast to the accuracy considerations of individual axes, the volumetric accuracy of a machine tool is determined based on measurement points distributed throughout the entire work envelope. Along with the positioning accuracy of the individual axes, this method also measures the effects of tilting movements, squareness errors and straightness deviations of the axes.

Positioning accuracy depends on position measurement

The measurement of the positions in the linear and rotary feed axes plays a definitive role here. If the axis positions are simply captured via rotary encoders on the motors, and are converted to the positions of the feed axes via gear reductions and the pitch of the ball screws, significant deviations between the control's machine model and the actual machine kinematics occur. These deviations result from thermal shifts in the ball screws and from transmission errors in the gears of the rotary axes, possibly leading to dramatic flaws on the workpiece, especially if produced with five-axis machining. The method of capturing the position via rotary encoders on the feed motors is also referred to as **semiclosed-loop operation**, since mechanical errors on the gear mechanisms cannot be compensated via the drives' control loops.

TELSTAR, the official ball of the FIFA world championship, with a perfect surface – milled in three machining steps.



Closed-loop operation of the feed axes with linear and angle encoders from HEIDENHAIN make it possible: precise machining of the seams despite large changes to the cutter orientation.

The positioning accuracy and repeatability values of feed axes can be vastly improved with the **use of precise linear and angle encoders**. Since the axis positions are no longer measured on the motor, but rather directly on the linear and rotary axes of the machine, this is referred to as **closed-loop operation**. If the machine tool's mechanical components are of sufficiently high quality, accuracies in the micron range can be achieved even under varying operating conditions. This results in enormous **advantages for five-axis machining**. The compensation movements can be traversed exactly if the cutter orientation is changed, without machining the workpiece contour incorrectly.

A soccer ball as proof of the TNC's accuracy

The advantages of capturing the position via linear and angle encoders from HEIDENHAIN become obvious when the Telstar workpiece is considered. Telstar is the name of the first civilian communications satellite, which NASA launched into space in 1962. The official ball of the FIFA world championships in 1970 and 1974 was named for the satellite, and has 20 white hexagonal panels as well as twelve black pentagonal panels. This pattern is still in wide use today.

The HEIDENHAIN workpiece is similar to the classical form of the Telstar ball. The ball was produced in three machining steps from a workpiece blank shaped on a lathe: three-axis milling of the pentagons with vertical paths and inclined cutter, three-axis milling of the hexagons with horizontal paths and inclined cutter, and five-axis milling of the seams.

Perfect surface quality and details demonstrate the accuracy of the machine

A perfect optical appearance of the Telstar ball is only possible if the seams, pentagons and hexagons are milled with superb precision despite a machining time of over two hours. The inclined angles prescribed for the cutter in the NC program for the Telstar tool result in large motions of the rotary and linear axes, necessitating a high volumetric accuracy. Transmission errors and thermal effects in the mechanics of the feed drives limit the volumetric accuracy of the machine if it is operated in semiclosed-loop mode. But if the feed axes are operated in closed-loop mode, the transmission errors of the drive mechanics are detected via the linear encoders on the linear axes and the angle encoders on the rotary axes, and can therefore be compensated by the control. The feed axes achieve a very high positioning accuracy and optimum repeatability over their entire traverse range. This makes precise machining of neighboring sections on the workpiece possible, even with large changes to the cutter orientation and substantial periods of time between the individual machining steps.

The potential for the volumetric accuracy of a machine becomes especially clear in the grooves that form the seams of the Telstar ball. With a cutter diameter of 25 mm and the slight groove depth of 0.15 mm, even errors of just ±10 µm or less would lead to obvious fluctuations in the groove width. The precision attainable when operating the feed axes in closed-loop mode is made very apparent at the intersections of the seams: despite the large changes to the cutter orientation in each of the seams, the intersections are hit exactly every time, thanks to the precision of the linear and angle encoders from HEIDENHAIN. +