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Responsive fixture design using dynamic product inspection and monitoring technologies for the precision machining of large-scale aerospace parts

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ABSTRACT

When machining a large-scale aerospace part, the part is normally located and clamped firmly until a set of features are machined. When the part is released, its size and shape may deform beyond the tolerance limits due to stress release. This paper presents the design of a new fixing method and flexible fixtures that would automatically respond to workpiece deformation during machining. Deformation is inspected and monitored on-line, and part location and orientation can be adjusted timely to ensure follow-up operations are carried out under low stress and with respect to the related datum defined in the design models.

1. Introduction

The manufacturing of airplane parts is characterized by large varieties and small batches. The increasing performance requirement of new airplanes imposes significant challenges to improving precision machining technologies. One of the difficult issues is the manufacturing of the large number of high-value structual parts in airplanes, many have thin-walls, are large in size and complex in shape. Significant effort has been devoted to the control of machining quality, and part deformation is regarded as the main cause of failure. Deformation is mainly the result of releasing residual stress when part material is removed during machining, where the material removal rate of large-scale aerospace parts may be as much as over 90%. Given a practical example, the deformation allowed is 0.50 mm for a beam part of dimensions: 6000 mm × 400 mm × 100 mm. This is very difficult to achieve in current practice because of part deformation problem.

In the traditional method as shown in Fig. 1, a workpiece is fixed tightly on the machine table by fixtures to ensure all the degrees of freedom are adequately restrained during machining [1]. The deformation of the workpiece is also restrained until all features of a setup are machined (see Fig. 1(a)). However, substantial deformation appears when the workpiece is unloaded after the roughing operation when large quantity of materials are removed (see Fig. 1(b)). For the follow-up operations (semi-finishing and finishing), blocks may be used to help locate and clamp the workpiece, and the datum may need to be adjusted to compensate the deformation in the bottom face (which is the datum surface in this set up) (see Fig. 1(c)).

The deformation may result in overcut by the follow-up machining operations. If the deformation is severe, the whole workpiece may be scrapped. A survey of this problem in aircraft structural part manufacturing carried out by the authors with Chinese aircraft enterprises revealed that the first-part-correct rate is less than 50% due to machining deformation using the traditional fixing and clamping method.

On-line process monitoring has been widely used as an effective way for in-process control of machining quality. For example, force sensors were used for cutting force or clamping force monitoring, acoustic emission sensors were used for tool wear monitoring, and acceleration sensors were used for

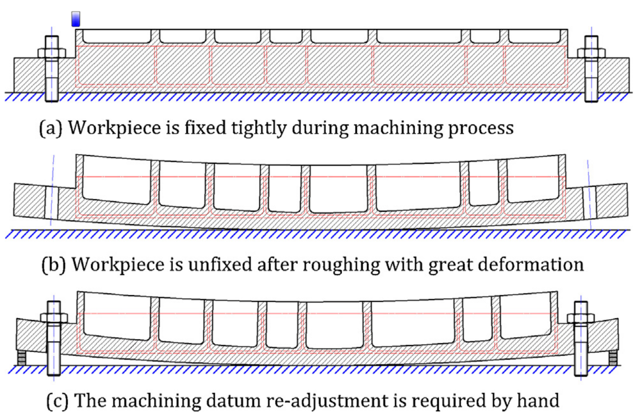

Fig. 1. The traditional workpiece fixing method.

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vibration monitoring [2–4]. Sensors were also used to monitor other process parameters such as presure distribution in micro-rolling, melt pressure and temperature in injection moulding [5,6]. Evanescent light was used to monitor the distance between diamond tool edge and workpiece surface [7]. Stress gauges were integrated with fixtures for monitoring clamping force to control operating pressure to the desired level [8].

Although on-line process monitoring has been effectively applied to machining process parameters, the monitoring of workpiece deformation is still a difficult problem. Because the workpiece is completely restrained in 6 degrees of freedom by traditional fixing method, part deformation changes as machining goes on, and will accumulate when the workpeice is released from fixtures after all machining operations are completed. This has been a major challenge for the precision control of large-scale aerospace parts. Analytical and numerical methods have been developed to predict deformation prior to machining based on the distribution of residual stress of material [9–11]. However, it is very difficult to accurately predict the residual stress of materials because of the difficulty in modelling the properties of workpiece material and the subsequent effect on plastic deformation, chip formation and separation [12].

This paper presents the design of a new fixing method to achieve low stress machining. The fixtures are flexible and can respond to the deformation of the workpiece and its constituent features as residual stress is released during machining. The deformation during machining are inspected and monitored on-line, either by a digitizing probe or by sensors. The information is used for the adjustment of the location and orientation of the workpiece, after each operation, rather than after all operations are completed. This ensures the follow-up machining operations are always carried out with respect to the CNC machine co-ordinate system, the machine table datum and the key functional features in the design model.

The proposed solution shifts the difficult problem of 'predicting' workpiece deformation, to the more factual problem of on-line 'monitoring' and 'inspection' of the workpiece deformation during machining, and timely adjustment of the machining strategy. The on-line inspection and monitoring devices are integrated with the machining tools and flexible fixtures, and are controlled responsively with reference to a dynamic product information model including interim features [13], which is a key means for the adaptive machining of high precision large-scale aerosapce structural parts.

2. The new fixing method for low stress machining

The principle of the new fixing method using the flexible fixtures is shown in Fig. 2. The workpiece is supported and fixed by a set of flexible fixtures, which can be adjusted to respond to workpiece deformation after each operation, i.e., the workpiece is always under low stress during the whole machining process. Note that the fixtures are only adjusted after one machining operation is finished, this avoids unstable situation during machining. The layout of the fixtures is determined by analysing the workpiece rigidity.

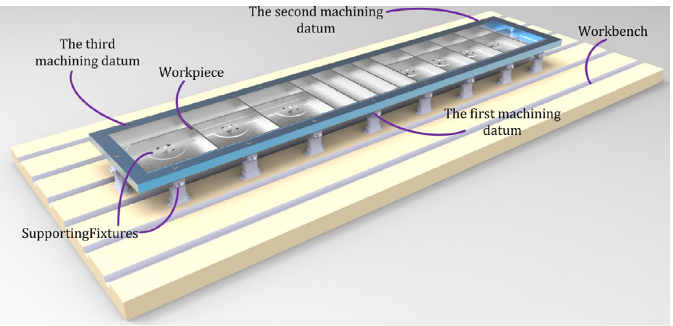

Fig. 2. The new fixing method for low stress machining.

For the example in Fig. 2, the workpiece is located by a horizontal face defined by 3 locating points (on 3 fixtures). One is used as the primary locating fixture (first datum), and is always clamped first. One vertical cylindrical pin (secondary datum) and one vertical diamond pin (third datum), which together form the machining datum. The horizontal face is also supported by all other fixtures which can be adjusted. As the material residual stress is released during machining, the location and orientation of the workpiece may be adjusted by the flexible fixtures, when severe or unbalanced deformation is mornitored by the on-line monitoring devices. The heights of the fixture supporting points on the workpiece can be adjusted to the appropriate level by the corresponding fixtures so as to get even allowance for the next machining step.

3. Design of the responsive fixture instrumentation

The stucture of the responsive fixture instrumentation and working principle is shown in Fig. 3. There are three movement tables: the movement table for the *Z* direction is controlled by an electronic motor, which moves up and down in response to workpiece deformation. The movement tables for the *X* and *Y* directions are realized by two electronic lead screws to respond to workpiece deformation in the *X* and *Y* directions, respectively. The electronic lead screw for the *X* direction is fixed in the movement table for the *Z* direction, and the electronic lead screw for the *Y* direction is fixed in the movement table for the *X* direction, hence the combined movement in the three directions can be realized.

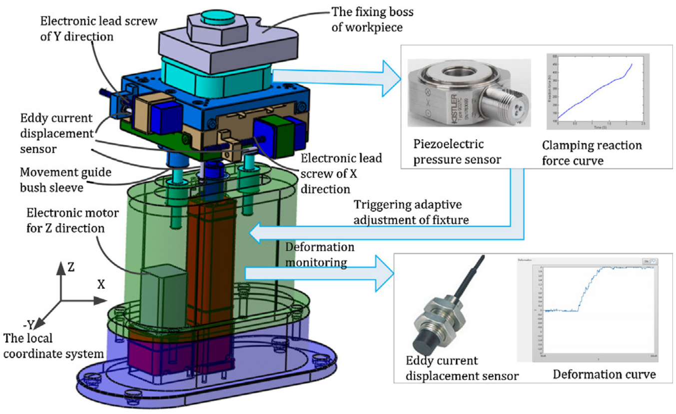

Fig. 3. The responsive fixture instrumentation and worknig principle.

When the workpiece residual stress is released, it tends to deform to reach a new balance. When the deformation is restricted by the fixture, it imposes forces to it, called reaction forces. The devices for monitoring the workpiece reaction forces are integrated into the fixture instrumentation. The workpiece reaction forces are monitored by piezoelectric pressure sensors located at the contact interfaces between the fixture and the workpiece, and the force directions are detected. The deformation in the three directons is monitored by three eddy current displacement sensors which are built in the fixture. The screw for joining the workpiece boss and the fixture is designed with different shapes: cylinder, cone or diamond for different workpiece locating purposes as needed. The clamping is performed by the electronic motor and the lead screw on the fixture. The workpiece reaction forces change during machining. The motion tables of the fixtures are controlled by PID (proportion integration differentiation) algorithms untill the forces are below preset threshold values, and motion directions are determined to reduce the reaction forces by taking advantage of the detected force directions. The deformation (the movement of the fixture tables) can be monitored by displacement sensors or inspection probes, and the allowed deformation value is determined according to the machining allowance and machining tolerance of interim machining states. The part information model is updated timely to reflect the changes in part geometry.