Robotics and Computer–Integrated Manufacturing 48 (2017) 209–218

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

A method to minimize the workpiece deformation using a concept of intelligent fixture

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ARTICLE INFO

Keywords:
Fixture
Active supports
Deformation
Distortion
Integrated system

ABSTRACT

Manufacturing processes are commonly affected by the low stiffness of the components limiting the quality and precision of the final product. Precision is one of the most important issues in the machining process, and the main cause for rejection is the part static deformation and the dynamic vibrations. The static deformation is mainly affected by two factors: deformation due to clamping and process forces, and geometrical distortions due to material removal and residual stress relieving during processing.

The deformations caused by the clamping in the fixture are normally associated to existing distortion in the raw workpiece due to previous manufacturing processes and to the clamping forces. These problems lead to uncertainties in the set-up process, hindering the fixture functions, the achievement of a right positioning of the workpiece and the avoidance of deformations due to clamping forces.

This paper presents an analysis to identify the causes of the static deformations during clamping and a method to correct the geometrical distortion and deformation of a clamped workpiece by the evaluation of the reaction forces in the selected relevant clamping points. It covers the design and validation of an active clamping unit to minimize the deformation produced by the fixture that could affect the machining process. The developed clamping unit presents an alternative to combine the locator and the clamper in a single component that controls the reaction force and the deformation of the workpiece in the clamping point, and it performs the positioning of that point to minimize the distortion of the workpiece. The clamping unit was verified in laboratory conditions and then tested in an industrial application, evaluating the capabilities related to positioning and reaction force control.

1. Introduction

The globalization and the intense competitiveness in the manufacturing industry pushes the companies to improve their processes and the quality of the manufactured products, minimizing the production costs and the lead time, especially in high added value sectors like aeronautics.

The manufacturing process in the aeronautic industry is normally affected by the low stiffness of the components designed to minimize the weight. The machining processes of this kind of components are driven by requirements affecting the integrity of the workpiece, the surface quality and the precision, as well as cost and lead time. These light and low stiffness components are normally obtained following 2 manufacturing chains: (i) by direct machining of a monolithic component removing up to 95% of the material of the raw part, or (ii) by welding different components made by other manufacturing processes (casting, forging…) and machined afterwards to obtain the final dimensions.

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http://dx.doi.org/10.1016/j.rcim.2017.04.005
Received 19 December 2016; Received in revised form 31 March 2017; Accepted 12 April 2017
Available online 25 April 2017
0736-5845/

Manufacturing processes (machining, welding, forging…) involve normally a combination of mechanical and thermal energy that generate residual stresses in the components [1,2]. Subsequent changes in the residual stress state by elastic, plastic or thermal deformation leads to a stress state modification potentially producing geometrical distortions of a component. Thus, the manufacturing of low stiffness components in the aeronautic sector can be significantly affected by distortions, as the residual stress changes can easily lead to deformation of the weak and flexible component.

The precision is one of the most important issues in the machining of aeronautics components, being the part deformation the main cause for rejection [3]. It is affected by the geometrical distortions that occur during processing, being that deformation related to the existence of residual stresses (internal forces) and clamping boundary conditions (external forces). In this situation, the origin of the geometrical distortion can be [4]:

- Deformation caused by a change in the residual stress state generated by previous manufacturing processes of the component. This is associated to the material removal during machining processes leading to a new internal equilibrium of the component.
- Deformation caused by external loads (clamping, cutting forces…) [5] that elastically deform the workpiece during processing, being recovered afterwards.

Attending to the second point indicated above, the fixture becomes a key component to avoid the geometrical error associated to deformation caused by external loads during machining processes. The fixture is a precision subsystem to provide an accurate positioning of the workpiece in the work space and to rigidly hold and support the component to withstand the machining forces, affecting the static and dynamic behaviour of the workpiece [6].

Fixture components can be divided into three classes by function: locators, supports and clampers [6]. The locators are in charge of correctly locate the component, establishing contact between these elements and relevant geometrical features of the workpiece, also providing support for the workpiece. The supports act like locators establishing contact with the workpiece, but the objective is not to locate the workpiece. Finally, the clampers provide the clamping force to fix the component ensuring the stability of the workpiece [5]. The clamping force is generated by the clamper and transferred through the workpiece to the locators, the supports and the fixed base (For example, the machine tool table). In this situation, the fixture layout affects the workpiece deformation, and it can be used to improve the machining accuracy by selecting suitable fixture layout and clamping force [5].

The most important criteria for the machining fixtures are positioning accuracy, workpiece stability, minimal workpiece displacement and deformation, and to avoid interference with the cutting tool [7]. Aeronautic components normally require dedicated fixtures instead of general purpose fixtures because of the complex geometry. The development of a suitable dedicated fixture in small batch production, like aeronautic sector, is driven by demanding requirements: accuracy, reliability and low set up time, so aspects like flexibility, reconfigurability, adaptability or automation become more relevant than pure economic issues [7,8]. The importance of the fixture is illustrated by its influence in the performance of the machining, with around 40% of rejected parts related to issues associated to the fixture design [9], and by the cost associated to fixture accounting for 10–20% of the total cost of a manufacturing system [10].

The effect of the fixture in the machining precision has drawn attention in the scientific community. Researchers have developed several methods and models for analysing the performance of a fixture. These works are the basis for the study of optimization of the layout of the fixture and they are normally oriented to improve the accuracy and to avoid dynamic problems, defining a new locator layout, the clamping sequence [11] or the clamping locations and force [7,12,13]. Different kinds of models (Analytical, finite element method, Genetic algorithms…) have been used to simulate the clamping process and its associated deformation [14]; these models depend on input parameters difficult to obtain or estimate making the simulation a complicated task [15]. In this field, some critical aspects include the initial residual stress distribution [3], the contact between the clampers, supports and locators with the workpiece [5], the clamping sequence [11], or the variable dynamic properties of the workpiece due to the material removal [16].

Fixture performance is usually affected by the manufacturing tolerances and the assembly process, limiting the precision of the predicted and designed behaviour. In this way, the setup accuracy of the workpiece is influenced by locators' layout, precise positioning and mechanical characteristics (stiffness, contact, pressure distribution…), being necessary to ensure a good contact with all the locators and the right functioning of the clampers and supports. These errors exist in practical use of fixture's locators, causing a locator displacement, which results in a workpiece displacement during the set up [5]. The influence of the fixture configuration and precision in the workpiece precise positioning has been analysed by different researchers [5,11,17–21].

Nowadays, sensors and monitoring technologies have evolved significantly allowing the on-line control of the actual state of the manufacturing systems [3]. The application of sensors in machining process includes a wide range of applications and uses [22,23]. Attending to the use of sensors in fixtures and clamping elements, the main objective is to achieve an active fixture; relevant bibliography review can be found in [6]. There are different reports including load cells, displacement sensors or strain gauges to monitor the clamping and reaction force [3,24,25], the workpiece deformation [3,26], or workpiece presence [27,28].

The use of sensors allows the identification of critical process conditions, but the objective is the compensation or correction of errors and process conditions, adapting the behaviour of the manufacturing systems to a desired and suitable situation. This requires the generation of alarms to alert the machine operator or the use of control systems connected to actuators able to produce an automatic correction of the manufacturing system, this is the use of mechatronic systems [29] and active fixtures [6].

A survey of the problems associated to the deformations in aircraft structural part manufacturing carried out with Chinese aircraft enterprises revealed that the first-part-correct rate is less than 50% due to the use of the traditional fixing and clamping method [3], so the use of active intelligent fixtures becomes an important improvement in this field in order to obtain automated, repeatable and reliable systems.

In the case of the development of intelligent fixtures, the use of mechatronic systems is a need using a combination of sensors, actuators and control systems, but it is not well developed. This topic of active intelligent fixtures has been reviewed by Fleischer et al. [30] and Bakker et al. [6]. Up to now, some applications have been reported but they are not developed at an industrial level being principally developments and applications in laboratory. This topic has been also treated in the INTEFIX project with different applications and ad-hoc developments oriented to solve problems of vibration, deformation and positioning in machining processes [31].

Regarding the active fixtures using force measurement some relevant works can be identified. [24,32] report the development of a modular and sensorized clamping unit using strain gauges and accelerometers to control the process force, the clamping force and the process vibrations; these contribution is able to measure the force exerted by the clamping element but it is not able to measure the reaction force because the support is not sensorized. In [33] the jaw distribution of a chuck based on the measurement of the clamping forces is presented being the objective the control of dynamic forces to avoid vibrations during machining. [34] introduces a prototype of intelligent fixture with active clampers able to provide a variable