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Experimental design and investigation of a pin-type reconfigurable clamping system for manufacturing aerospace components

A Al-Habaibeh^{1*}, N Gindy² and R M Parkin¹

¹Mechatronics Research Centre, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

²School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, UK

Abstract: This paper presents an experimental design and evaluation of a pin-type universal clamping system. The clamping system is designed for holding complex-shaped aerospace components, such as turbine blades, during machining processes. The experimental investigation is performed by comparing the pin-type clamping system with a dedicated clamping system during the machining of aluminium and steel parts. Force signals are monitored during machining. The experimental results are presented and compared with a dedicated clamping system. From the comparison, the performance of the clamping system is discussed. The results provide an evaluation of the designed pin-type clamping systems for machining operations. The results prove that the pin-type clamping system can be reconfigured for machining different complex shaped components with performance comparable with a dedicated clamping system.

Keywords: fixturing, aerospace, reconfigurable clamping system, pin-type clamping system, machining, low-melt alloy, phase change material

1 INTRODUCTION

The major forces influencing today's aerospace manufacturing environments are not different from other manufacturing industries: global competition, shortened product life cycle, increasing requirements for quality and reliability, faster paced advances in increasingly complex technology, rapidly expanding options in materials and processes and increased unpredictable surroundings. The ability of an aerospace enterprise to take advantage of these forces is the key to any successful aerospace manufacturing strategy. The overriding goal of the manufacturing enterprise is to achieve rapid flexible integrated design and manufacture of innovative products in batch sizes that are getting smaller at a price the customer is prepared to pay [1]. To thrive in the emerging aerospace market condition it is therefore important that the manufacturing enterprise should be capable of rapidly responding to market trends by utilizing intelligent technology within a rapid product development

environment capable of very short times to market. To meet such requirements, technological advances have been made during the past few decades with respect to machine and cutting tools. Nevertheless, the fixturing technology in machining is still lagging behind despite its criticality and importance.

Fixturing has been considered as one of the main problems to improve flexibility, productivity and part quality, particularly in the aerospace industry. It is one of the most direct threats to cost effectiveness and operational efficiency. Fixturing is used for locating and restraining the workpiece in position and to ensure that dimensional accuracy is maintained during manufacturing operations. If perfection could be achieved, fixturing could be produced at a high speed and have the ability to hold any complex part. Generally, in manufacturing environments, fixture design is based on past experience and trial-and-error approach. Therefore, fixturing design is expected to be a long process with prohibitive cost. Many fixturing techniques have been investigated during the past few decades (see, for example, references [2] to [4]). The majority were developed to meet changes in manufacturing industry. Fixturing systems can be divided into dedicated modular contact fixturing and pin-type fixturing systems.

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**Corresponding author: Mechatronics Research Centre, Loughborough University, Holywell Building, Holywell Way, Loughborough, Leicestershire LE11 3UZ, UK.*

A dedicated fixture is a single-purpose device which is designed to locate and constrain a specific part or component. Once the manufacturing process is completed, the fixture is then stored for later use. This traditional approach is costly and time consuming since it requires a special fixture to be manufactured for every part or component. These drawbacks have motivated researchers to develop modular fixturing system [5, 6]. A modular fixturing system is a fixturing system that uses a collection of reusable standard components to construct a complete variety of special-purpose work-holding devices. It reduces fixture manufacturing time, makes fixture modification easier and eliminates dedicated fixture storage space. Modular fixture design was mainly based on trial and error until the development of computer systems to aiding the design process [5, 7]. Computer aided fixture design ranges from expert systems [8] to a kinematics approach [9] to using genetic algorithms [10]. Contact fixturing system utilizes magnetic fixturing, instant freeze chucks and phase change fixturing system [11, 12]. The main problem in using magnetic work-holding methodology in aerospace manufacturing is that the fixture should take the shape of the component which results in the same problems of dedicated fixturing. Also residual magnetism could be a problem in cleaning the swarf off the component. Instant freezing chucks [12] can hold any material by placing the component on a plate covered by a thin film of water. When the chuck is switched on, the water freezes, holding the component. Phase change fixturing is based on the ability of certain materials to change from a fluid to a solid and back to a fluid again [13]. When material is in liquid phase, the part is immersed to the required depth. Then the material's solid phase is introduced, providing rigid support and work-holding force for the component. Upon finishing the manufacturing procedure, the component is removed

by reversing the phase of the work-holding material. The main advantages are holding complex shape components with uniformly distributed forces. The main disadvantage of this technique is the possible contamination from the phase change material and the difficulty of machining the immersed parts of the component.

2 PIN-TYPE FIXTURING SYSTEMS

2.1 Overview

A pin-type fixturing system has been documented in several patents during the past 30 years [14–18]. A pin-type fixture can be used for locating and clamping of a workpiece of irregular shape during manufacturing processes. The main concept of a pin-type fixture consists of a main body or base that contains a two-dimensional array of orthogonal to the base rods or pins which protruded upwards through the surface and can be moved upwards and downwards individually, either manually or by springs or by fluid pressure, and then clamped or locked in position so that the tips of the rods form a cradle conforming to the shape of the workpiece, in which the workpiece is fixed for manufacturing operations. Figure 1a presents a generic schematic diagram of the main concept of a pin-type fixture.

Different locking mechanisms have been suggested in the literature including mechanical methods, pneumatic pressure, hydraulic pressure and phase change material. The expected advantages of a pin-type fixture is the uniform distribution of forces and the reconfigurable shape.

2.2 The proposed pin-type clamping system

Figure 1b presents the designed and manufactured pin-type clamping system under evaluation. The clamping

Fig. 1 (a) The main concept of a reconfigurable pin-type clamping system; (b) the designed and manufactured pin-type clamping system

system consists of two platforms. Each platform has a two-dimensional array of rods or pins (14×8). The pins have a diameter of 5 mm and the platform dimensions are $150 \text{ mm} \times 100 \text{ mm}$. The pins' matrix has dimensions of $110 \text{ mm} \times 60 \text{ mm}$. The pins end with a round tip in order to avoid scratching or stamping the workpiece. The platforms are made of steel and the rods are machined from a brass rod. A low-melt alloy (bismuth–lead–tin–cadmium) is used as the holding mechanism. The ability of this material to change phase at a relatively low temperature within about 4 min makes it a suitable option for the design. The low-melt temperature allows the use of hot water or induction heating as the power source of phase change. One of the main aims of the design is to produce the fixture as simply and as inexpensively as possible. The rods were cut from a standard pipe. The low-melt alloy has provided the locking mechanism for the pins. The aim of the clamping system is to provide a new, inexpensive and simple universal fixture for rapidly and easily holding or supporting many variations of complex contoured parts of irregular shape during machining or any other manufacturing processes or actions. The clamping system is aimed at providing a rigid fixture by the use of phase change material as a means of locking the rods' mechanism. The invention eliminates the using of separate fixtures to hold multiple or complex parts. It consequently eliminates the fixture manufacturing time, cost, maintenance, storage and set-up costs associated with using different fixtures for different parts. The clamping system also has the advantage of holding parts of the same shape but with a wide tolerance by using the reconfigurability of the fixture.

Three main issues are tested in this paper:

- (a) the applicability of the pin-type clamping system concept (i.e. can the clamping system be used for milling operations?);
 - (b) the reconfigurability of the clamping system (i.e. the use of the same clamping system to machine different components);
 - (c) the rigidity and stiffness of the clamping system compared with those of a dedicated clamping system.
- The previous points were implemented using the optimum clamping forces which can produce maximum clamping forces without causing any distortion to the workpiece.

3 EXPERIMENTAL SET-UP AND PROCEDURE

The experimental work in this study was performed in four stages to verify the initial design capabilities. The experimental investigation was performed using a conventional computer numerical control (CNC) milling machine and the Variax HexacenterTM, a parallel kinematic machine tool. Table 1 presents the main four test stages which were conducted to evaluate the clamping system.

3.1 Testing the applicability and reconfigurability of the pin-type clamping system

The first two tests in Table 1 are performed in order to ensure that the clamping system can be easily used for holding complex parts for machining processes. Figure 2 presents the first two tests: applicability and configurability of the clamping system. Figure 2a presents the reconfigurability of the same clamping system to machine the root of an aluminium blade using a conventional CNC machine tool. Figure 2b presents the machining of an aerofoil of a generic steel blade

Table 1 The implemented four stages to test the designed clamping system

Tested criteria	Description	Machining parameters
Test 1: Applicability of the pin-type clamping system	The clamping system is used to machine grooves in the root of an aluminium blade (see Fig. 2a)	Feed rate = 200 mm/min Axial depth of cut = 1 mm Radial depth of cut = 10 mm Spindle speed = 1500 r/min Cutter type = 10 mm slot drill
Test 2: Reconfigurability of the pin-type clamping system	The clamping system is reconfigured to locate another steel blade for machining its profile (see Fig. 2b)	Feed rate = 2 m/min Axial depth of cut = 0.5 mm Radial depth of cut = 0.2 mm Spindle speed = 1200 r/min Cutter type = 32 mm round insert face milling cutter
Test 3: Rigidity and stiffness	Clamping system is reconfigured to locate an aluminium rectangular workpiece and to compare its surface roughness when using a dedicated clamping system (see Fig. 3)	Feed rate = 200 mm/min Axial depth of cut = 5 mm Radial depth of cut = 10 mm Spindle speed = 1500–4000 r/min Cutter type = 10 mm slot drill
Test 4: Rigidity and stiffness	Clamping system is reconfigured to locate a steel rectangular workpiece and to compare its surface roughness when using a dedicated clamping system (see Fig. 3)	Feed rate = 50 mm/min Axial depth of cut = 5 mm Radial depth of cut = Spindle speed = 250–1250 r/min Cutter type = 10 mm slot drill

Fig. 2 The first two experimental stages of the evaluation process (tests 1 and 2 of Table 1)

using the Variax Hexacenter. The orientations of the generic blade and the machined surfaces are described in Fig. 2.

3.2 Testing the rigidity and stiffness of the pin-type clamping system

In order to test the rigidity and stiffness of the pin-type clamping system, a comparison between machining force signals and surface roughness values of a product machined using the pin-type clamping system and a dedicated clamping system is performed. The workpiece is chosen to be a rectangular shape with the following dimensions: 100mm length, 50mm width and 12mm depth. The flat top surface of the workpiece of width 12mm was machined for testing. The positioning and orientation of the workpiece are as shown in Fig. 3. The cutting force signals are monitored using a three-component platform dynamometer (Kistler 9257A) which is connected to one side of the evaluated clamping system (see Fig. 3). The dynamometer is connected to a

three-channel charge amplifier (Kistler 5001). The signals are monitored using a fast data acquisition card (National Instruments AT-MIO-64E-3). Figure 3 presents photographs for the experimental set-up of the pin-type clamping system and the dedicated clamping system.

Machining of aluminium and steel workpieces are used to compare the two clamping systems. The machining parameters are shown in Table 1. In addition to the clamping and machining forces, the average surface roughness R_a and the maximum roughness height $R_{y_{max}}$ were measured along the y axis (see Fig. 3), to compare the rigidity of the clamping system.

4 RESULTS AND DISCUSSION

Tests 1 and 2, as described in Table 1, showed that the pin-type clamping system is capable of holding workpieces for machining operations. Also, the clamping system is successfully reconfigured to hold a different

Fig. 3 The experimental set-up to measure clamping and machining forces for the pin-type clamping system and a dedicated clamping system (tests 3 and 4 of Table 1)

geometry by reheating the low-melt alloy and clamping it around the new workpiece. The pin-type clamping system is successfully used to machine the root of the aluminium blade and the aerodynamic profile of another steel blade. However, in order to evaluate the rigidity and stiffness of the clamping system, tests 3 and 4 are performed in order to compare a dedicated clamping system with the pin-type clamping system and to measure surface roughness and forces.

Surface roughness was measured for the selected machining parameters. The R_a and $R_{y_{max}}$ values were measured on a length of 0.8 mm on the machined surface. Figure 4 presents the results for the two clamping systems for machining of aluminium and steel. The maximum measured values in the y direction of R_a and $R_{y_{max}}$ of the machined surface (see Fig. 3) are compared. It has been found that the pin-type clamping system has a higher surface roughness than the dedicated clamping system when machining aluminium at a high spindle speed (r/min). However, the pin-type clamping system has a better characteristic when machining a steel workpiece at a lower spindle speed. However, the range of R_a

values between both clamping systems in the two tests is about $5\mu\text{m}$ only. The variation could be due to the natural frequency of the complete fixturing–dynamometer system. The variation in the level of machining forces is found to be greater for the steel workpiece (measured as the power of the cutting forces). This could explain the reason why the surface roughness values of the aluminium part are less than the surface roughness values for steel for both clamping systems. Since R_a is measured along the y axis, the surface roughness increases with increasing power of the F_y signal, as shown in Fig. 5. Higher forces and vibration leads to higher surface roughness which could be a result of the insufficient rigidity of the clamping–dynamometer system (see Fig. 3).

5 CONCLUSIONS AND FURTHER WORK

The designed pin-type clamping system is found to be flexible and reconfigurable to be used for holding complex aerospace parts during machining. The pin-type

Fig. 4 The surface roughness measurements of (a) aluminium and (b) steel workpieces

clamping system has been found to show a slightly better response for low cutting speeds of steel than the dedicated clamping system. This is indicated in an improved surface roughness and lower power level of cutting forces. However, the dedicated clamping system is found to have a relatively better response when machining aluminium at a high cutting speed. This could be due

to the natural frequency of the pin-type clamping system which is expected to be lower than that of the dedicated fixturing system. However, more analysis is needed on the basis of real manufacturing parts to evaluate its suitability for real machining environments. The future work will include a simulation and experimental investigation of the design parameters, namely the number of pins, the

Fig. 5 The relationship between the F_y signal and surface roughness for aluminium and steel workpieces

distribution of pins, the pin diameter, the pin length and the pin material.

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