Mechatronics 46 (2017) 101–114

Contents lists available at ScienceDirect

Mechatronics

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

A helical milling and oval countersinking end-effector for aircraft assembly☆

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ARTICLE INFO

Article history:
Received 2 March 2017
Revised 8 June 2017
Accepted 12 July 2017

Keywords:
Aircraft assembly
Drilling
Helical milling
Oval countersinking
Multifunction end-effector

ABSTRACT

In order to meet the high quality, reliability and high efficiency requirements of aircraft assembly, a new multifunction end-effector (MFEE) is developed, which integrates three functions: drilling, helical milling and oval countersinking. After an introduction to the design of the MFEE, the working principle of automatic oval countersinking is discussed in detail, which has rarely been studied before in literature. The architecture of the whole drilling system is elaborately presented, and particular emphasis is put on the key techniques to guarantee hole quality, which are hole position compensation, normal vector adjustment and countersinking depth control. Finally, results of drilling experiments conducted on aluminum 7050-T6 alloy and titanium Ti–6Al–4 V alloy are presented. It is shown that the system could improve the assembly quality and drilling speed of aircraft components effectively. The position accuracy could be controlled within $\pm$ 0.5 mm, the normal direction accuracy was better than 0.5°, and the countersinking depth variation could be controlled within 0.02 mm at the worst case, all the machined holes and oval countersinks satisfy both the geometric dimensions and surface roughness.

1. Introduction

In the aerospace industry, mechanical joining methods with rivets and bolts are widely used due to their high reliability. Drilling fastener holes is a labor intensive and costly task for aircraft assembly [1,2], for example, around 1 million holes should be drilled for the assembly of an Airbus A300, and for a Boeing B747 this number is 3 million. The machining quality of the holes should meet a high standard since it is closely related to the fatigue life of an aircraft, about 80% structural failures are resulted from fatigue damages from the joint part of the aircraft structures [3]. Therefore, the technology of machining riveting and bolting holes influences not only assembly efficiency, but also performance and safety of aircrafts.

As the aerospace structures develop towards thinner wall, higher integration, and more complex shape in order to guarantee longer life, higher quality and higher fuel efficiency, the demand on advanced hole drilling technology gets higher and higher than ever before. Meanwhile, the increasing large usage of hard-to-machine materials such as Carbon Fiber Reinforced Plastics (CFRP), Ti-alloy, raises difficulty on hole drilling. For traditional hole drilling methods, tool wear in the drilling of Ti-alloy may cause large exit burrs and large cutting force in the drilling of CFRP may lead to material delamination and avulsion [4], which are main reasons for scrapped parts. Therefore, great efforts have been made to develop new drilling technologies for aircraft assembly in the aerospace industry.

Automatic drilling and riveting technologies are widely adopted in aircraft assembly due to their high efficiency and reliability. Single drilling end-effector coupled with an industrial robot has been utilized in the assembly of aircraft for a long time [5]. Novator developed a portable orbital drilling unit and exploited the advantages of orbital drilling, which has been successfully used on the Airbus final assembly line [6]. In cooperation with Novator, Boeing studied orbital drilling technology for the drilling of hard-to-machine material stacks [4,7]. In academia, a lot of researchers studied both advantages and disadvantages of orbital drilling compared to the conventional drilling. Whinnem et al. [7] pointed out that the hole depth is limited to only about 40 mm for orbital drilling, and due to the eccentric rotation, the tool would shake which causes decline in the hole quality and shorter tool life. Axial cutting force generated in orbital drilling is smaller than that gen-

☆ This paper was recommended for publication by Associate Editor Wolfgang Kemmetmüller.

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http://dx.doi.org/10.1016/j.mechatronics.2017.07.004

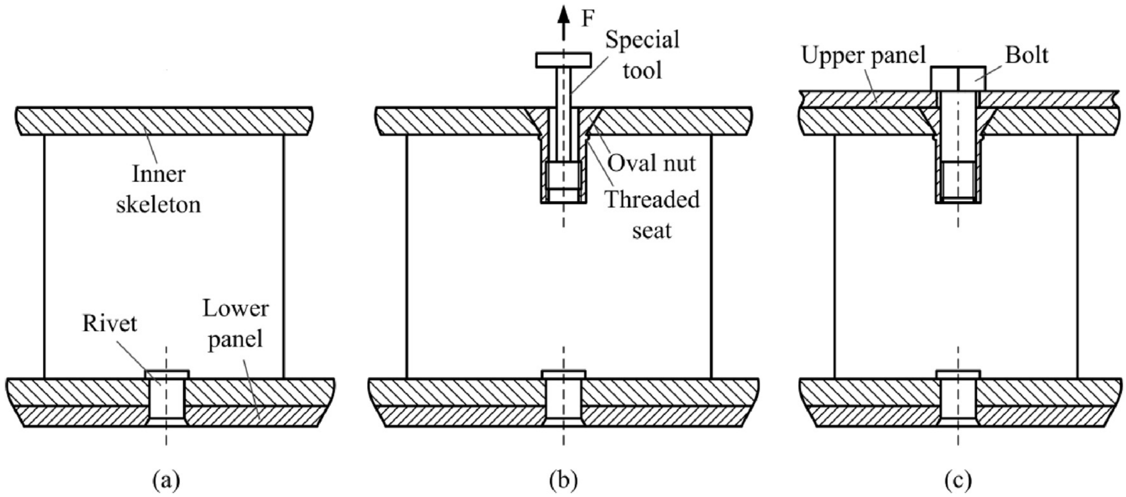

Fig. 1. Schematic of wing panel assembly. (a) Lower panel joined with inner skeleton with rivet; (b) oval countersinking on inner skeleton and fasten oval-head nut with special tensioning tool and (c) cover upper panel and join with inner skeleton with bolt.

erated by conventional drilling, therefore orbital drilling allows the use of low-cost standard industrial robots for drilling holes in the aerospace industry, which can achieve the required hole tolerances [8]. Deitert [9] studied the bending force caused by the friction between the blade and material in orbital drilling, which would cause non-linear distribution of hole diameter along hole depth. All the unique characteristics of orbital drilling process were examined in [10] from a new energy perspective, the results showed that orbital drilling possesses advantages over conventional drilling in hole quality, due to the smaller axial force and lower cutting temperature, resulting from the redistribution of the load exerted by cutting edges and the cooling effect of the unstable rotational air flow in the tool-workpiece annular gap. Brötje accomplished the tasks of automatic drilling, countersinking, sprigging and riveting under the cooperation of two industrial robots [11].

In addition to drilling and countersinking of round holes, the countersinking of oval shapes may also be necessary for aircraft assembly. For example, in order to improve performance and reduce weight, the wing panels adopt up-down integrated structure, which consists of an upper panel, a lower panel and an internal skeleton. During the wing assembly illustrated in Fig. 1, the lower panel and skeleton should be connected together first through bolts or rivets, and then the upper panel is covered. An airtight space is formed by the three components, the upper panel cannot be directly connected to the skeleton through bolts or rivets, and it can only be fastened unilaterally. Since only one-sided fastening is allowed, there is no access space for wrench and riveter on some of the key parts, oval-head nuts shown in Fig. 2 are necessary for the joining. There are four types in total, named NAS3, NAS4, NAS5, NAS6, NAS is short for National Aerospace Standards. Inside the oval-head nut, there exists threads and ring grooves. The nut can be securely fastened with special tensioning tools acting on the inner ring grooves. During the fastening process, the oval-head of the nut protects it from self-rotating, a threaded seat is formed on the internal skeleton, and long-term tightening effect and reliable joining are achieved. After the upper panel is covered on the inner skeleton, it can be directly connected to the oval-head without ear nut via bolt since the thread inside the nut makes unilateral joining of the upper panel to the inner skeleton possible. The working principle of oval-head without ear nut is illustrated in Fig. 1. Compared with the installation of conventional bolts and rivets, the significant difference of installing the oval-head nut is that oval countersinking must be performed on the workpiece.

Fig. 2. Oval-head nuts (with threads and ring grooves inside).

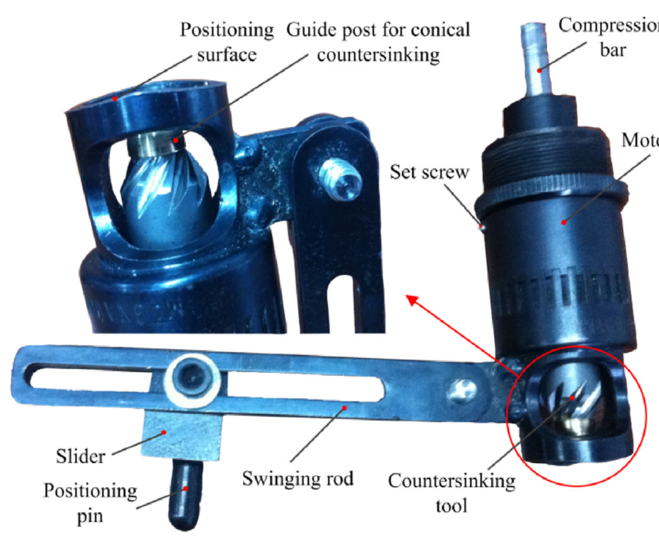

Fig. 3. Manual oval countersinking tool.

In manual installation of the oval-head nut, a special countersinking tool is used (Fig. 3), which consists of a positioning surface, a positioning pin, a slider, a swinging rod, a set screw, a motor and a compression bar. Combined with different cutters, the countersinking tool can be used to perform different types of oval coun-