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Smart drilling for Aerospace Industry: state of art in research and education

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Abstract

In this brief survey, the use of smart manufacturing (SM), specifically in drilling aerospace industry, is discussed and the state of art is presented. Generally, SM is based on real time monitoring for adapting parameters, a challenge for the industry of the forth revolution. During drilling stack composites for aerospace, the monitoring tool force and power can identify the cutting material, within a determined uncertainty envelop of tool wear. The control of machining process can improve tool life, manufacturing productivity and quality. This paper presents a review of drilling strategies used on smart manufacturing used for drilling composites. The actual actions for educating future engineers that will use this research and industrial technology are pointed out and a summary of main challenges is presented.

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Keywords: Smart manufacturing; Machine data collection; Tool wear optimization; Drilling; Metal-composite structures.

1. Introduction

Metal-composite hybrid structures have become essential in aeronautical construction for economic and environmental reasons as maintain good mechanical properties. Due to the different assembled materials, which have a distinctly different machinability, the parameters must change during machining to allow this optimization [1].

In the past, the procedure for optimizing cutting parameters were time disconnected to the manufacturing process. With all the connectivity of machines, automation and networking, now-a-days in the focus of Industrial internet of things (IIoT), the real-time identification of parameters for improving the process is an industrial reality [2, 3].

The political environmental protection initiatives related to aerospace industry (laws, and directives) push researchers to

reduce times and costs, increase the efficiency and to develop flexible and smart processes [4]. It is a fact that thousands of holes have to be drilled for assembling aeroplanes, so smart drilling is a key point for performance maximization. Increasing the feed rate or cutting speed on the layer that presents higher machinability is directly related to this goal [5].

Smart drilling is, so, the adaptation of the cutting parameters in real time, which requires the characterization and modeling of the evolution of the process variables (forces, torque and power depending on the cutting feed and spindle speed), the creation and management of a database, the processing of data and real-time adjustment of the machining parameters [6,7]. These models are associated with the capacity for identification, data processing and real-time action offered by machine learning tools [8].

Axial drilling is the most useful machining process for assembling subassemblies, however, the savings in production cost with this process remain limited, in particular due to the damage to the composites during drilling, problems with burrs in metals, and non-optimal operating conditions due to multi-material stacking. Low frequency vibration-assisted drilling (LFVAD) [9, 10] is a good solution in these cases because of its capacity of chip control and thanks to lower temperatures during drilling due to non-continuous tool-work piece contact.

Orbital drilling is actually an helical milling operation used to produce holes in difficult-to-cut materials, such as Carbon Fiber Reinforced Polymer (CFRP), Ti-alloys, hard materials, and other aerospace materials [11]. This technological innovation reduce damage and burr comparing to axial drilling [12]. In this case, the tool trajectory, cutting speed, feed and cutting geometry relationship allows higher flexibility on parameters choice and also a longer cutting time [1]. This process brings potential gains, in terms of quality, but it must be optimized to achieve higher productivity.

It is clear that with innovation, new qualification of aerospace industry employees are needed. This scenario requires that research is directly connected to education for offering different and actual competences for machining. Students should experience the possibility of flexibility and control of parameters during the process [13].

The objective of this article is to present a panorama of smart manufacturing applied to axial and orbital drilling aerospace work pieces. In these specific examples, as similar work developed by Wenkler et al. for milling processes [2], the average specific cutting force is the calculated variable for the identification of materials and control of cutting parameters.

Nomenclature

a_p	Axial depth of cut (mm ²)
A_c	Chip load area (mm ²)
b, db	Cuting edge length and cutting edge elements (mm)
D	Nominal tool diameter (mm)
f_z	Feed per tooth (mm/th)
F_c^I	Cuttting force for one cutting edge (N)
h	Uncut chip thickness (mm)
k_c	Specific cuttting force (MPa)
P_c	Cuttting power (W)
R_P	Distance from point P to tool axis (mm)
V_c	Cuttting speed (m/min)
$V_{f,xy}$	Feed velocity in the plan xy (mm/min)

V_{fz}	Vertical feed velocity (mm/min)
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2. Drilling Processes in Aerospace Industry

2.1. Typical materials in Aerospace

The need of cleaner energies is one of the most important challenges on aeronautic industry. Electrical and hybrid aircrafts autonomy is limited by the weight, thus, the relation resistance-weight in aerospace industry as weight reduction in transport systems can impact in carbon emissions over the life of the transport system [14]. Therefore, materials used in aerospace industry are mainly aluminum alloys, titanium alloys and CFRP.

It is important to notice that both alloys have low machinability and also machining CFRP is a challenge. It should understand the chip removal mechanisms, orientation of cutting forces in relation to the fibers, different mechanisms of tool wear and delamination on the workpiece [5].

In the aerospace industry, plates are non-homogeneous materials, stacks of CFRP plates with metallic plates to build the aircraft bodies parts [15]. Because the material properties are different, the machining processes and chip formation are special. The transition between materials can be identified during axial drilling, as k_c is different between two materials along the cutting edge, as in orbital drilling it suddenly change the average cutting force. For CFRP, the identification of the specific cutting force is more difficult because of the anisotropic distribution of fibers and more disperse behavior of forces [16]. In this brief article, for simplicity the identification of aerospace fiber materials will not be enlightened; nevertheless it is a second step on the research project.

2.2. Drilling processes and strategies

Different drilling processes are used in industry, and especially in aeronautics. Conventional axial drilling is the most common process for the machining of a fastening holes in the aircraft industry and is usually named 'conventional drilling'. This well-known process is nevertheless still difficult to control and make it reliable. Chip evacuation is one of the main issue in the industrial context. Monitoring the tool wear is another one, to ensure the quality of the hole drilled. The control of the diameter, of the burr, of the surface roughness is always a challenge. And it becomes even more difficult when drilling multi-material stacks [17]. Drilling metallic alloys such as titanium or aluminum, together with composite-fiber laminates, with the same tool and the same cutting conditions remains an issue. To solve some of these problems, other drilling processes have been developed or used.

Another recent drilling process is the vibration-assisted drilling (VAD), based on the addition of small oscillations to the feed motion of the tool. It permits to ensure the chip fragmentation and thus to ease its evacuation. It brought an important advantage in terms of reliability of the drilling operation, also for multi-material stacks even if the issue of cutting conditions remains.

Orbital drilling is a more recent process, corresponding to helical milling. It presents many advantages compared to the conventional process such as avoiding or at least limiting, the burr formation and delamination in composite laminates, and allowing a better chip evacuation. It remains less productive considering one operation, but may permit to reduce the number of operations to finish the hole. As axial drilling, orbital drilling encounters the problem of cutting tool and cutting conditions choice for multi-material stacks.

Conventional drilling tools without vibration assistance do not represent a good solution considering the cost-quality for machining aerospace materials [5], but axial drilling is easier for modelling and identification and prepares to an adaptation to LFVAD. So, in this article it will be presented the identification of materials for controlling the cutting velocities in axial drilling and in orbital drilling.

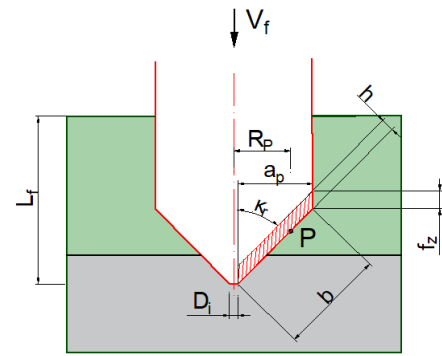


Fig. 1. Axial drilling (transition between two plates)

2.3. Cutting power and forces in axial drilling

In homogenous material, the specific cutting force k_c is determined experimentally for a pair tool-workpiece. It is a function of the cutting speed, depending on its range, but the cutting material primarily influences it, for a given tool. That it is the reason, this is the key parameter for indirect material identification in the present article [2].

Experimentally, the specific cutting force k_c (MPa) can be calculate using cutting force for a single cutting edge F_c^1 (N) data, given the known uncut-chip load area A_c , a sum of the chip load for every element from the cutting edge db . If the un-cut chip thick is constant, the chip load area is the feed per tooth f_z multiplied by the axial depth of cut a_p .

$$k_c = \frac{F_c^1}{A_c} = \frac{F_c^1}{\int_0^b h(b) db} \quad (1)$$

The cutting force cannot be acquired directly from the machine data. Only if the machine is instrumented with piezoelectric sensors or a dynamometer, it will be useful for the control. Also, for drilling the cutting force of a single cutting edge is usually in opposition to the second cutting edge, so the sum is, in theory, zero.

In order hand, specific cutting force can be calculated using the cutting power P_c (W) and the cutting speed V_c (m/min). Cutting power, Torque and the spindle speed N (rpm) are variables that can be read from the machine tool CPU because internal sensors measured it by default.

For a fixed conventional drilling tool with two cutting edges and a nominal diameter D (mm), the specific cutting power, considering both cutting edges, is calculated as:

$$k_c = \frac{60 P_c / 2}{\int_0^b V_c(R_P) h(P) db} = \frac{60 P_c}{V_c(D) f_z \frac{D}{2}} \quad (2)$$

where the cutting speed is calculated as a function of the distance R_P from P to the tool axis. As the uncut chip thickness is constant and the cutting edge is straight, the specific cutting force is a function of the external diameter D . The cutting speed when $R_P = D$ is:

$$V_c = \frac{\pi D N}{1000} \quad (2)$$

Figure 1 shows the cutting geometry for the axial drilling. It is clear that in the transition, the cutting force will be an integration along the cutting edge and it will have one part from material 1 and another from material 2 [15]. This transition is used in data processing as a trigger for identifying a new material and as soon as the signal is stabilized, new parameters are calculated and the cutting speed and feed are up-dated in the loop and into the program.

One important characteristic that induces error on the material identification is the evolution of the specific cutting force with tool wear [18]. The drilling force from the cutting lip (inner diameter D_i) is not negligible after tool wear and it can add an additional parcel to the consumed power. In addition, cutting forces are higher and it could induce the recognition algorithm to identify a transition or a different material. It is necessary to build a calibration model, considering tool wear and the range of cutting parameters for material identification.

2.4. Cutting power and forces in orbital drilling

Different from axial drilling without vibration-assistance, in orbital drilling, the cutting edge are not all simultaneously in contact to the workpiece. The cutting force and cutting power depends on the cutting process geometry. Orbital drilling is a circular milling process with vertical displacement. Figure 2 shows the cutting geometry for circular milling. The active cutting edges depends on the radial depth of cut and the relation between drilled diameters and nominal diameter. In the case of the transition between two materials, the different materials affect a different parcel of two cutting edges. That is why, the rough signal from power or from cutting force cannot be used for direct identification and fine data treatment is needed for the trigger.

Fig. 2. Circular milling, an approximation for orbital drilling.

Once the tool is engaged only in one material, the average cutting force (and the average radial force) can be used for calculating the specific cutting force and material identification.

The modeling of forces and its dynamics is well described in [19, 20]. The cutting force and power is calculated as a milling process where the feed velocity has two components: $V_{f_{xy}}$, that produces the circular trajectory (a function of the feed per tooth, spindle speed and the difference between drilling diameter and tool diameter), and V_{f_z} that actually produces the drilling. Each cutting edge has three cutting parts: central part, axial part (with negative K_r in order to be able to allow the tool to dive) and the radial part (similar to end milling tool with $K_r=90$). The uncut chip thickness varies along the cutting edge and it is necessary to integrate locally to calculate the cutting force of each cutting edge.

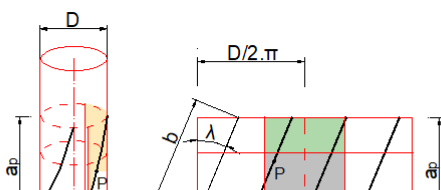
3. Smart manufacturing strategies for Industrial application

A smart manufacturing system includes smart machine tools (SMT) or intelligent machine tools (IMT) [3]. The SMT were developed with the I-Iot and intelligent sensors with remote service, condition monitoring, fault diagnosis, maintenance, and management of the machine tool. The SMT could be a robust commercial machine tool or even a small driller machine. The IMT adds upon a SMT a new generation of artificial intelligence technology which is capable to generate, accumulate and utilize its own knowledge.

The two possibilities, SMT and IMT, could be used for smart drilling, it is necessary an implementation of a Smart Machine Controller (SMC) in an adaptable architecture that satisfies both commercial and open source CNC controllers [21,22]. A SMC approach was done by Park et al. [23] that optimized feed rates to minimize machining time by using an autonomous machining system based on a reference force calculated with input data and NC simulation.

It is important to notice that, in aerospace industry, the use of Automatic Drilling Units (ADU) with an on-board intelligence can be used for changing the cutting parameters.

In this first simplified proposition it is used a MT with a commercial I/O communication protocol (a Siemens SINUCOM NC-Trace software connected to the PROFIBUS) and an input loop for changing the machine-tool parameters. As the frequency rate of the MT output data is limited, the experiments should be designed to have material transition that could be recognized by the system. Another problem is to



calibrate the signal to have a small noise-signal relation to be able to identify the parameters change.

4. Connection Smart drilling innovation and teaching

It is important to foster a relevant innovation that will make European SMEs competitive towards foreign companies that sometimes operate in favorable national contexts (lower taxes, labor costs, subsidies, etc.). This innovation is not possible without a training of the workers to the new technics.

In the case of smart drilling this training must be very practical to make the users aware of the differences and of the improvements, but also to make them master the different parameters. To reach this goal digital tools such as learning games are foreseen to outreach as soon as possible the results of smart manufacturing strategies.

The training of students is also very important and requires thinking upstream of a synergy between research laboratories and universities.

One good example is the *Maison de la Formation Jacqueline Auriol* (MFJA) : it is a tri-fold structure consisting of training, research, innovation and technology transfer that it is dedicated to aeronautics and aerospace lies at the heart of the Aerospace Valley cluster. In the MFJA, all the practical courses of the *Université Fédérale Toulouse Midi-Pyrénées* for manufacturing and aeronautics engineering, hosted under the same roof. This synergy occurs between the INSA-Toulouse, the Institute of Technology Paul Sabatier, the Smart Association (Systems, Manufacturing, Academics, Resources, Technologies) and the ISAE-Supaero to train future technicians and engineers [24].

Inside the MFJA structure is being built a smart machining cell that will form future engineers and develop I-Iot skills on the next industry generation. Smart drilling activity will be included due to its connection to local industry.

5. Conclusion

Some aspects concerning the use of smart drilling in aerospace industry at its relation to the teaching activities have been concisely reviewed. An overview of different materials and strategies for drilling is presented, specially the main characteristics of axial drilling and orbital drilling. A glance of the real time monitoring based on the specific cutting force is described for application to drilling stack composites. It is pointed out the importance of the additional practice activities to engineering students using new research technologies.

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