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Characterization of residual stresses induced by a multistep hole making sequence

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Abstract

This paper investigates the evolution of residual stresses induced during a three steps hole making sequence (drilling => boring => reaming) that enables to manufacture accurate holes. The objective is to characterize how the 1st and 2nd operations may affect the final surface integrity. Surface residual stresses induced by each step are analysed by X-ray diffraction. It has been revealed that the first roughing operation (drilling) determines the thickness of the final affected layer, whereas the residual stress state in the external layer is controlled by the last operation (reaming). Reaming induces a compressive layer in the external layer. Finally it has been shown that boring does not contribute significantly to the final residual stress state.

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Keywords: Residual stresses, reaming, drilling, boring, sequential cuts

1. Introduction

Aircraft structures are composed of many components. To assemble these components, screws and rivets are used, which requires numerous holes on each part. Considering holes as stress concentration areas, they determine the component's lifespan.

Nowadays, it is well known that fatigue resistance is strongly correlated with 'surface integrity', that is a concept including the surface topography (i.e. surface roughness), as well as the microstructural state and the residual stress state of the subsurface [1-6]. Holes are manufactured by a wide range of cutting and superfinishing processes (drilling, gun drilling, boring, reaming, burnishing, honing, abrasive flow machining, ...) that may be used either alone or combined within a sequence so as to fit the specifications. High accuracy holes in aircraft components are commonly obtained by making a preliminary drilling operation so as to remove a big

amount of material (roughing operation) (Fig. 1). Then a boring operation is performed in order to improve the cylindricity and to calibrate the depth of cut for the final operation (Fig. 1). Finally a reaming operation is applied so as to calibrate the dimension, the cylindricity and the surface roughness of the functional surface (Fig. 1). It can be stated that the specifications of aircraft components are concerned with the macroscopic geometry (diameter, cylindricity) and by the surface roughness. Most of the time there is no specification related to microstructure and residual stresses. Nevertheless, the impact of these parameters is considered with the fatigue impact certification test. However, it is clear that these parameters are of primary importance as far as fatigue resistance is concerned [1]. In the current state of the art, there is no scientific method that enables to predict the residual stress state induced by such a sequence (drilling→boring→reaming). Some preliminary works have started to develop numerical models to predict the residual stress state induced by drilling [7-8]. However these models are far from being accurate.

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Moreover, they do not model neither boring, nor reaming operations. So, nowadays, it is not possible to predict the final residual stress state after such a sequence. It is also not possible to predetermine which cutting operation, among these three cutting processes, is responsible for the external residual stresses (compression or tension ?) and for the depth of the affected layer (10 μm , 100 μm , more ?). Moreover the designers of aircraft component only consider residual stresses through the certification test. So it becomes necessary to develop models that make it possible to predict the evolution of the residual stress state induced after each step of the sequence, so as to improve the design of these components.

Before developing a model able to predict residual stresses induced by these three processes, this paper first aims at experimentally quantify and weight the effect of each cutting process on final residual stress state. After that, the focus of the development of the future model will be concentrated on this process (processes), instead of trying to model cutting processes that are of secondary importance on the final surface integrity. A second objective is to identify the situation of the residual stress fields after each step (tension \leftrightarrow compression, affected depth) as well as the interaction between each cutting process (effect of history).

Previous works have already tried to analyse experimentally or numerically the interaction of a sequence in turning [9–12], but none of them were concerned with hole making. It is only possible to report some preliminary experimental works in drilling by [13, 14].

The present work has been conducted on a sequence (drilling \rightarrow boring \rightarrow reaming) applied on a martensitic stainless steel 15-5PH.

Table 1 : Cutting conditions and commercial designation of cutting tools

	DRILLING	BORING	REAMING
Cutting speed (m/min)	52	15	5
Feed (mm/rev)	0.17	0.116	0.18
Theoretical diameter (mm)	14,7	14,9	15
Theoretical depth of cut (mm)	/	0.1	0.05
Commercial name of the tool	Walter Titex perform DC150	Seco CCMT 060204 F1 CP500	Mapal High performance reamer, solid carbide coated-HP421
R_β (μm)	/	35	5
Corner radius R_e (μm)	/	400	/
Back Taper ($\mu\text{m}/\text{mm}$)	/	/	0.7-0.9
Number of edges	2	1	6
Lubrication	Internal and external	No	Internal and external
Lubrication type	Emulsion	No	Emulsion
Lubrication pressure	40 bars	/	40 bars

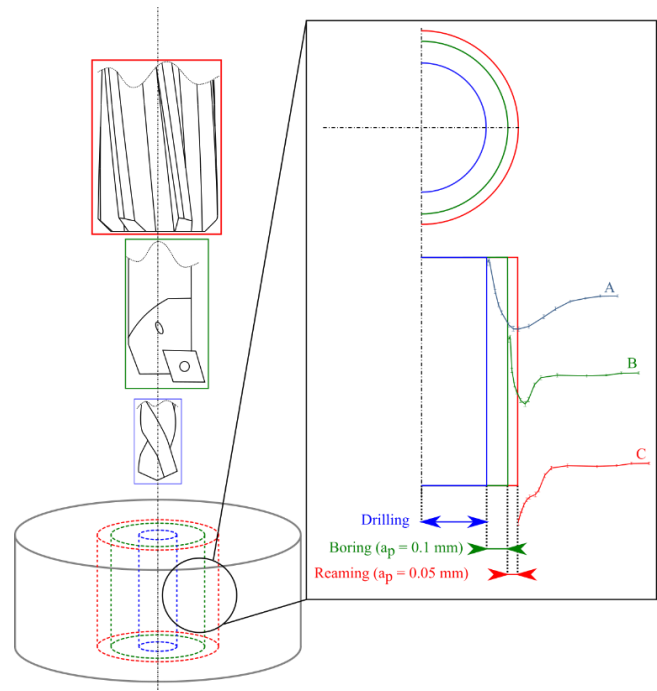


Figure 1 : Cutting sequence of a hole and axial stress distributions beneath the surface

2. Experimental method

An experimental work has been conducted so as to characterize the residual stress state induced by each cutting process of the sequence. The designations of the three commercial tools are presented in Table 1, as well as their cutting conditions in accordance with an industrial case study.

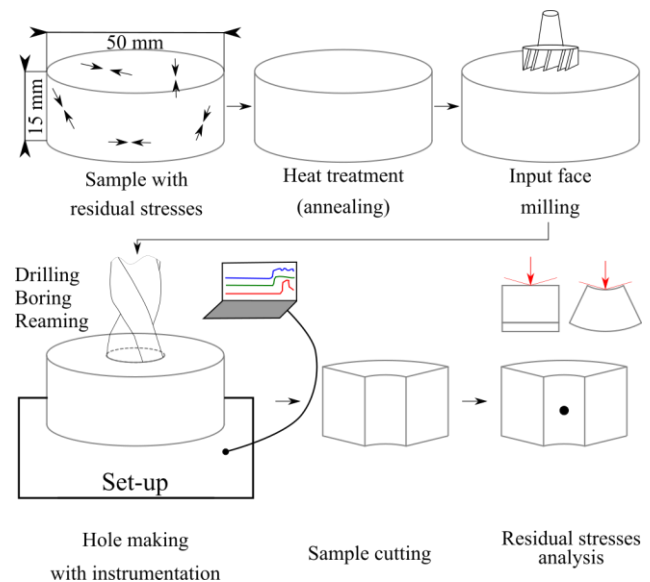


Figure 2 : Test procedure

The measurement of residual stresses in a hole is not a standardized method. It requires customized developments. The method applied in this paper has been developed by Girinon et al. [15] and illustrated in Figure 2. It consists first in preparing a sample with a heat treatment (400°C/4h + slow cooling with a nitrogen shield) so as to release bulk residual

stresses. Then the surface is prepared by a soft milling operation so to ensure a stable drilling operation. After the through hole is made following the cutting sequence. Then the sample is cut with a smooth handsaw to avoid heat generation. The cutting of the sample seems to be of secondary importance considering the measurement of the final residual stresses [15]. Finally the residual stress state is analysed in the middle of the hole (stable cutting conditions in this area) by X-Ray diffraction in the axial and circumferential directions with the same measuring conditions proposed by [13].

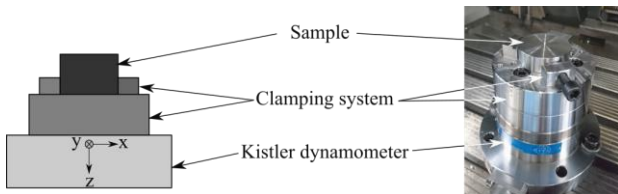


Figure 3 : Experimental set-up

The axial cutting force F_z and the torque M_z have been measured during each operation thanks to a dynamometer Kistler 9272A as shown in Figure 3. An example of force and torque evolution are plotted in Figure 4.

Samples have a 50 mm diameter and a 15 mm height. Tests have been replicated three times for each cutting process so as to evaluate the deviation of residual stresses. This means that 3 samples have been machined by drilling before being analysed. Then 3 additional samples have been machined by drilling+boring. Finally 3 samples have been machined by drilling+boring+reaming.

3. Residual stresses analyses

Figure 5 plots the evolution of axial and circumferential residual stresses. For each step, 3 residual stress curves have been measured. These 3 curves have been replaced by a cloud including the highest and the lowest values of residual stresses. The cloud takes into account the measuring uncertainty of the X-ray machine and the variation of the measured forces. This way of presenting residual stress curves enables to evaluate the deviation of experimental results and limits the risk to propose wrong conclusions based on scattered results. In Figure 5, the blue cloud plots the residual stress curves corresponding to the drilling step, then the green cloud plots the results obtained after drilling+boring. Finally the red cloud presents the final residual stress state after the full sequence (drilling+boring+reaming). Two ways of presenting the results are available. On the left side (Fig. 5a), the curves are plotted starting from the external surface, whereas on right side (Fig.5b), the curves are plotted by considering the shift of the surface induced by each cutting operation. This last way of presentation, proposed by [10], has already been used in Figure 1, so as to facilitate the understanding of the interaction between each cutting process (effect of history).

NB: The shift of each cloud takes into account the actual average depth of cut and not the theoretical one.

3.1. Interaction between cutting processes

Figure 5a shows that the affected depth in drilling is around 150 μm whereas it is only 50 μm for the two other

operations. When observing Figure 5b, it becomes obvious that

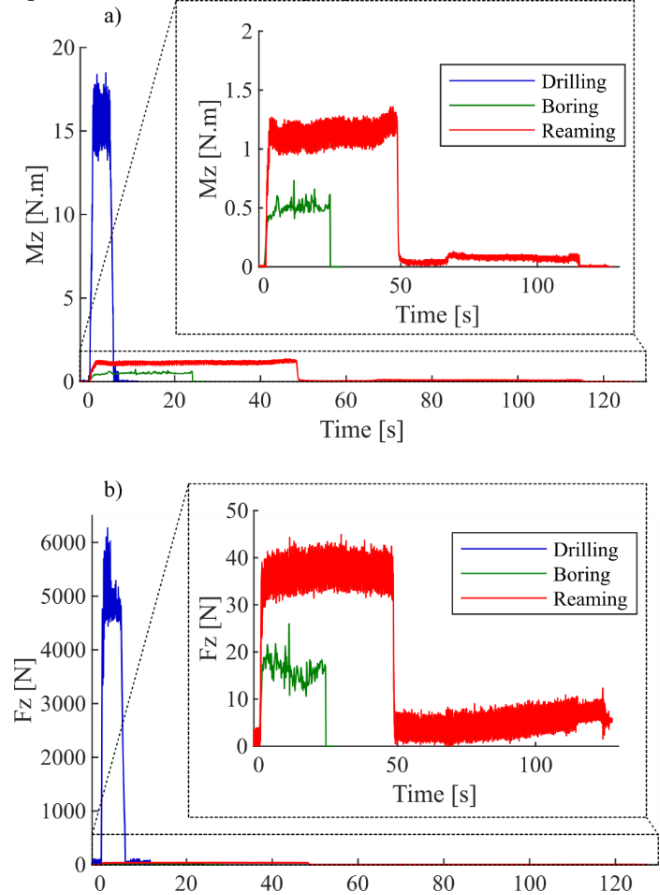


Figure 4 : Evolution of torque M_z (a) and feed force F_z (b) in drilling, boring and reaming

this wide affected layer after drilling may influence the final residual stress state in the subsurface after boring and reaming. On the contrary, boring can not influence reaming as the depth of cut in reaming is higher than the affected layer in boring (50 μm affected depth after boring \Leftrightarrow 60 μm measured depth of cut in reaming).

So as to conclude on the possible interaction of drilling on residual stress profiles after boring and/or reaming, another experimental campaign has been performed. First, a heat treatment (HT) has been introduced after drilling so as to evaluate the residual stress state induced by boring without the memory of drilling. With the same strategy, a heat treatment has been made after drilling+boring, so as to evaluate the residual state induced by reaming without considering the effect of history. These results are presented in Figure 6. It can be observed that the two clouds (with or without a preliminary heat treatment) are very similar. There is only a small difference for the clouds in the axial direction for boring. The cloud is something more shifted towards compression when a HT has been applied (Figure 6a). This effect is not related with the residual stress state induced by drilling, as this roughing process tends also to shift the curves towards compression in this region. So the contrary would have been expected if an interaction would have been significant. It is possible to conclude that this small variation for boring is only due to a natural deviation of the experimental tests. It is also possible to conclude that boring induces its own residual stress profile independently of the drilling process.

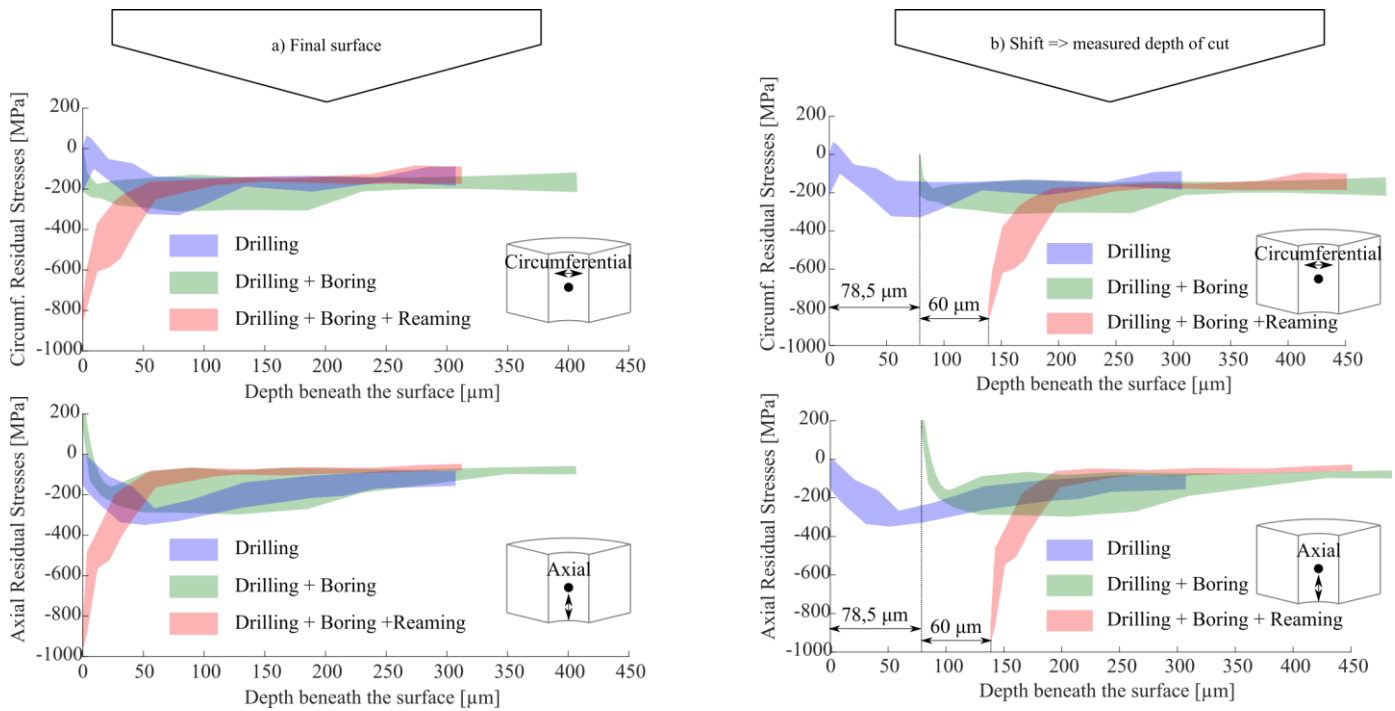


Figure 5 : Residual stresses on the final surface (a) and shift by measured depth of cut (b)

By observing Figure 6b, it is obvious that reaming induces also its own residual stress profile independently of the boring process, as there is no effect of the preliminary heat treatment.

So this section enables to conclude that, as far as residual stresses are concerned, there is no interaction between the three cutting processes in the present case study. So it can be concluded that the final surface integrity, that is responsible for the fatigue resistance of a component, is determined by the reaming process.

3.2. Shape of the residual stress profiles

This section is devoted to the analysis of the shape of residual stress profiles. Figure 5 shows that drilling leads to a tensile stress state in the external layer, followed by a peak of compression to get an equilibrium. The same shape is observed after boring with a different magnitude. This kind of residual stress profiles are typical for cutting processes involving a combination of thermal (heat generation by plastic deformation and friction) and mechanical (plastic deformation) actions, but with a dominant effect of the thermal action (high temperature in the surface) as shown by [1]. Similar curves have been obtained after turning of a 15-5PH by Mondelin & al [16]. It seems that the contribution of drill edges, drill margins, and of boring inserts exhibit similar thermo-mechanical phenomena as the ones observed in turning. The difference of magnitude between the two residual stress clouds (affected layer 150 μm in drilling ⇔ 50 μm in boring) is correlated with the much lower level of energy involved in boring compared to the one in drilling. It is clearly observable in Figure 5 through the much lower level of torque M_z and feed force F_z in boring. In addition Table 2 shows the average value of torque and the corresponding cutting power P (equ. 1) involved in the process. The small amount of energy consumed by boring is probably the main explanation for this thinner affected depth.

$$P = M_z \times \omega \quad (1)$$

With P : cutting power (W), M_z : torque (N.m) and ω : spindle speed (rad/s)

By observing the residual stress profiles induced by reaming, they reveal a fully different shape. This process induces a strong compressive layer (≈ -800 MPa) in the external surface. Reaming differs strongly from boring with a larger number of edges (6 edges in reaming ⇔ 1 edge in boring) and with a much thinner uncut chip thickness (25 μm in reaming ⇔ 63 μm in boring). This kind of residual stress profiles is typical of processes having a dominant mechanical action, such as burnishing as shown by [1]. It is confirmed by the analysis of the evolution of the force F_z and of the torque M_z (Figure 4), as well as of the cutting power P (Table 2). Reaming induces a higher mechanical action but with a much lower cutting speed (15 m/min in boring ⇔ 5 m/min in reaming), which induces a high plastic deformation and limits the level of temperature in the machined surface. This is beneficial to induce compression in the external surface. A similar statement has already been made by [17] when comparing the residual stress profile induced by turning or by ball burnishing for the same 15-5PH steel.

Table 2 : Power of each operation

	M_z (N.m)	ω (rad/s)	P (W)
Drilling	15	117	1770
Boring	0.5	33	16
Reaming	1.2	11	13

4. Conclusion

This paper aims at investigating the evolution of residual stress profiles induced by a hole making sequence composed by a drilling, a boring and finally a reaming operation.

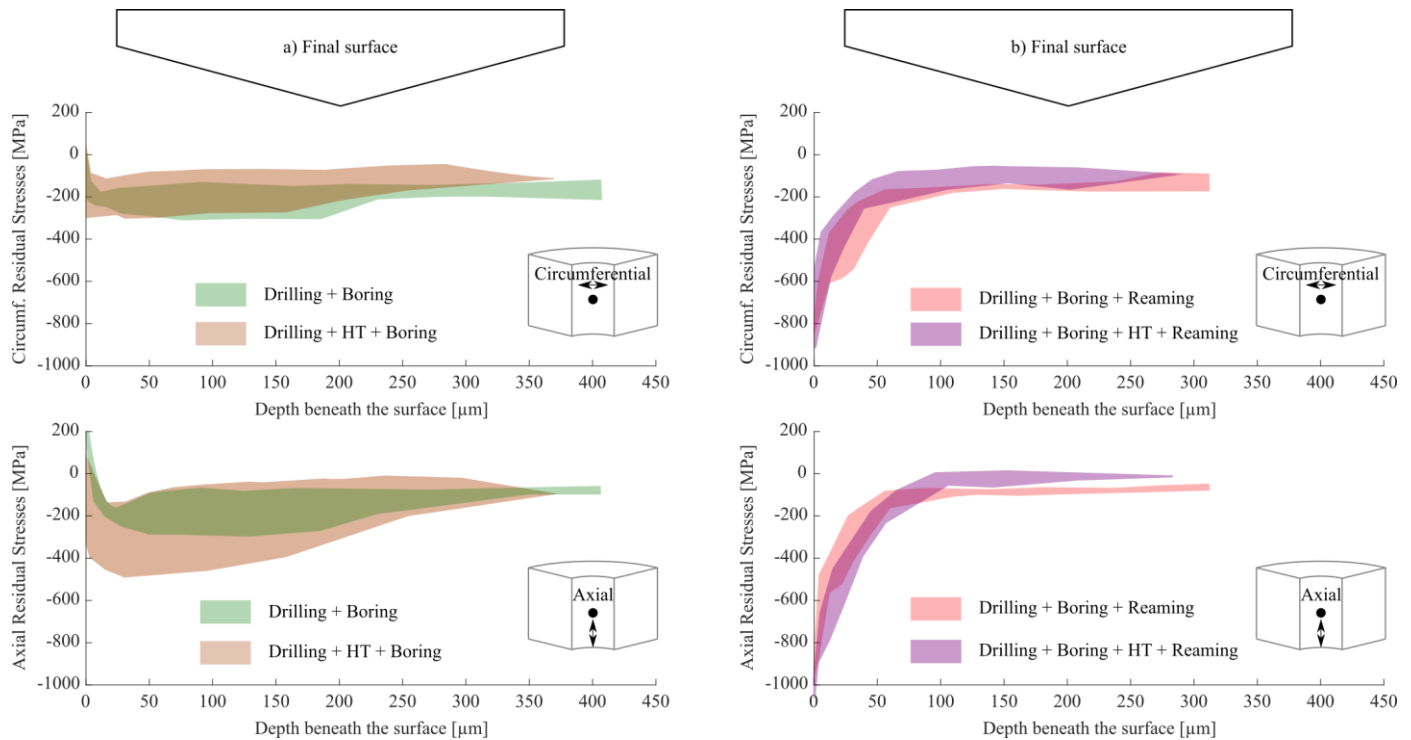


Figure 6 : Comparison of residual stresses preceded by HT in boring (a) and in reaming (b)

It has been shown that drilling is the most aggressive cutting process leading to tensile stresses in the external layer with a peak of compression in the subsurface. The affected layer is thick. The boring process leads to a similar shape but with a different magnitude. Especially the affected layer is three times smaller. These two processes have a dominant thermal influence on the final residual stress state.

On the contrary, the reaming process induces a strong compressive residual state within a rather thin depth. This process has a dominant mechanical action.

Finally, it has been shown that none of the previous cutting processes (drilling, boring) have an influence on the final residual stress profiles. Reaming is the single process determining the final surface integrity.

So, for the future numerical model developed to predict residual stresses induced by this hole making sequence, only reaming will be taken into account. Thanks to this experimental work, the key process and physical phenomena that should be involved in the future model are highlighted.

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