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Numerical simulation of the reaming process in aluminium 2024-T351 – Analysis of the evolution of the material stress state

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ABSTRACT:

In aircraft assemblies, holes for fastening are critical areas from where fatigue damage can be initiated, especially for metal parts. Depending on the operating conditions of the various stages of the machining process of the hole (drilling, reaming, cold expansion, second reaming), the manufacturers observe significantly different fatigue strength of the structures. To optimize the behavior of the aircraft assemblies, the manufacturers want to understand the impact of the whole machining process of the hole on the material characteristics of the part. They investigate particularly the residual stress state in the hole edge zone which can be significantly different depending on the operating conditions.

This paper investigates the influence of the reaming process in an aluminum 2024-T351 part with initial material state not clean of mechanical stress. Indeed, before the final reaming, the parts undergo at least a drilling operation, and sometimes a cold expansion operation. For this study, in collaboration with Airbus, the simulated reamed part has been pre-stressed by the cold expansion process. Both processes are simulated using a finite element model with Abaqus. The implemented strategy to simulate the reaming process is based on the progressive deactivation of mesh elements. The obtained results show a low relaxation of the circumferential and radial residual stresses in the part during the reaming simulation.

Keywords: Reaming, numerical simulation, residual stress, aluminum

1. INTRODUCTION

Fastening holes in mechanical structures are critical areas for the initiation of fatigue damage, especially for metal parts. The experimental study of fatigue strength and failure modes of bolted joints made of aluminum alloy parts is the subject of a lot of experimental works [1-5]. Different failure modes are observed. Some failure occurs in the bearing mode, with cracks initiating at the edge of the hole and others occurs in the fretting mode, with cracks initiating away from the hole boundary. Residual stress fields at the vicinity of the hole have an impact on the fatigue performance of holed parts [6, 7]. Compressive residual stress result in a significant increase in the fatigue lives. Indeed, this kind of stress induces a closure effect on the crack whereas the tensile residual stress results in an opening effect on the crack. Thus, in the aeronautical industry, processes have largely been developed in order to introduce a compressive residual stress field at the vicinity of the holes [8]. Interference fit fastener [9-11] or cold expansion process [12-16], which consist in introducing a conical mandrel with a high level of interference, allow to improve greatly fatigue life of aluminum alloy joints. Compressive residual stress fields introduced by these two processes are well known to be extensive and to reach high values. However, other processes involved in the machining of the fastener hole, such as drilling and reaming, also leave a region of disturbed material along the edges of the hole that can cause a residual stress field. Even if these induced residual stress fields are much lower than those left by a process such as cold expansion, they affect the fatigue behavior of the holed part [17]. Therefore, they need to be better apprehended in order to be accounted for the life-prediction methodology.

Generation of residual stress during machining is a complex phenomenon to simulate numerically. It involves both mechanical and thermal phenomena. On the one hand, simulation of metal cutting, which is associated with large strains, requires Eulerian methods. On the other hand, the prediction of residual stress, which needs knowledge of the loading history of each material particle, requires Lagrangian methods. Thus, several authors choose to develop « decoupled » numerical models, composed of a first model simulating the cutting, allowing them to obtain an equivalent thermo-mechanical loading, which they apply in a second model directly on the finished part. This is for example the case of Girinon [18], who, in his work on numerical simulation of drilling in hard metals, develops a rigid ALE model of material removal, then extracts the thermal loading on the part which is then applied in a second model purely Lagrangian. Others authors, as Ozel [19] in his work on the simulation of the turning of hard metals develops a unique Lagrangian model with an updated software in which chip separation from workpiece is achieved with continuous remeshing. Still others, such as Valiorgue [20] who works also on the turning of hard metals, free themselves from the modeling of material cutting by experimentally identifying the thermomechanical equivalent loading to apply in their Lagrangian model. Finally, other authors adopt even simpler reaming modeling strategies. In order to simulate the reaming process after cold expansion in their finite elements model, Achard [21] and Huang [22], choose to simply deactivate the mesh elements located in the reaming zone of the workpiece and Chakherlou [23] and Ismonov [24] choose to reduce the stiffness of the elements near the hole to almost zero.

This paper focuses on the numerical study of the modification of the stress state of an aluminum 2024-T351 part during the reaming process which has been weakly studied. This alloy was selected because of its use in the majority of the current fleet of commercial aircraft. Most authors studying the numerical simulation of machining processes consider a material devoid of mechanical and thermal stress. However, in the aeronautical industry, parts do not present a zero stress state before reaming since they undergo at least a drilling operation, and sometimes a cold expansion operation. Thus, it is interesting to carry out a study on the impact of the reaming process taking into account the history of the loads applied to the part. For this, a numerical model considering a pre-stressed part is developed. The initial stress state of the part is introduced through the simulation of the cold expansion process.

2. NUMERICAL MODEL

The Finite Elements Model (FEM) representing the cold expansion process developed with Abaqus by Achard [21] is taken over and adapted to the expansion in an aluminum alloy part in order to generate a stress state in the part before reaming. The model, presented in Figure 1, represents the workpiece and the different parts of the tooling : the conical mandrel, the sleeve and the jaw.

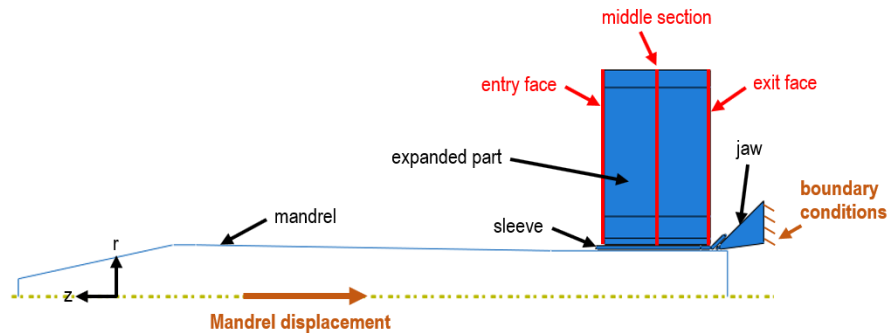


Fig. 1. Finite element model of the cold expansion process

All the parts respect the dimensions imposed by the industrial specifications to obtain a final hole diameter of 6.84 mm and the thickness of the part is 6 mm. The simulated expansion rate is 6% in order to generate important residual stress fields in the part to better observe the influence of the reaming process in the rest of the study. The model is 2D axisymmetric, the part geometries, the loadings and the boundary conditions being compatible with this behavior hypothesis.

2.1. MATERIALS

2024-T351 aluminium alloy is widely used in the aircraft industry for its low density, high fatigue performance and high damage tolerance. This alloy is precipitation strengthened, its mechanical properties are determined by a heat treatment (T3) applied to the material after its shaping. This heat treatment induces the controlled precipitation of some material phases and so an increase in mechanical properties by obstructing movement of dislocations. According to the microstructural characterization of 2024-T351 alloy lead by Huda [25], the high mechanical properties of this alloy are associated to three types of inclusions: Al-Cu, Al-Cu-Fe-Mn and Al-Cu-Fe-Si-Mn.

The T3 heat treatment refers to a three-stage treatment: solution heat treated, quenched and naturally aged. The T-51 treatment indicates that after quenching, the material is stress relieved through controlled stretching (plastic deformation of about 2%).

In the numerical model, the mechanical behavior of the parts is defined according to different constitutive laws, the parts having different materials. The steel mandrel can be considered and modeled as a rigid body in relation to the expanded aluminium part. The material data of the three other parts have been provided by Airbus and are confidential. Therefore, they are not presented in the paper. However, a graph representing the constitutive laws of the parts without units is presented for illustration purposes in Figure 2. The elastic behavior of these three parts is considered as isotropic. The steel jaw which undergoes only weak plastic strain is modelled with a simple elastic constitutive law. The mechanical behavior of the steel sleeve and the aluminum workpiece which undergo severe plastic strain is described by elastoplastic constitutive laws. The plastic behavior of the workpiece is modelled by a linear kinematic hardening and the plastic behavior of the sleeve is modelled by an isotropic hardening.

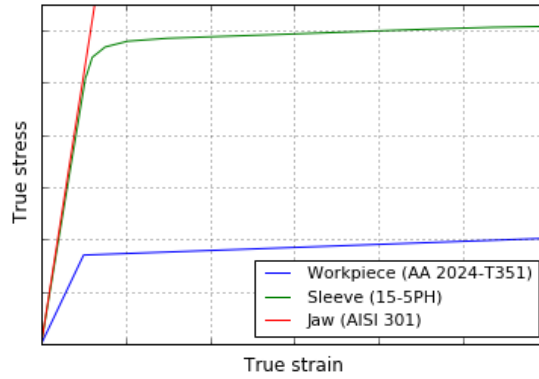


Fig. 2. Constitutive laws of the numerical model parts

2.2. COLD EXPANSION SIMULATION

In order to simulate the kinematics of the expansion, a displacement of -40 mm along the model axis of revolution (z) is imposed on the mandrel and the lower face of the jaw is fixed. This boundary condition is sufficient to ensure the correct positioning of all the parts between them. Indeed, the axial forces applied on the sleeve and the workpiece during cold expansion simulation are recovered by the fixed jaw through the contact areas. Four contact areas are considered with a “surface-to-surface” discretization method. A contact area between the inner surface of the sleeve and the mandrel is defined with a very low friction coefficient (0.005) in order to apply a reasonable axial load on the sleeve and to consider the split of the sleeve. Indeed, in practice the sleeve is split which limits the axial load applied to the sleeve. A contact area between the outer surface of the sleeve and the workpiece and between the sleeve and the jaw is defined with a friction coefficient of 0.1 in order to ensure the correct positioning of the parts. A friction coefficient of 0.1 is chosen to simulate the contact between the mandrel and the jaw.

The calculation step corresponding to the simulation of the cold expansion process with the axial displacement of the mandrel is followed by a step simulating the withdrawal of the sleeve which is called “recovery”. During this step, the contacts between the elements are deactivated and no loading is applied. This allows the part to achieve a new stress state.

2.3. REAMING SIMULATION

The residual stress state obtained from the expanded part after the recovery step constitutes the initial stress state for the simulation of the reaming process.

Reaming is simulated by deactivating mesh elements through the “Model change” interaction in Abaqus. This option allows to ramp down to zero the forces and fluxes that the region to be removed is exerting on the remaining part of the model at the nodes on the boundary between them. To simulate reaming in the model, the deactivated elements are located in a band along the height of the part at the hole edge with a width of 0.35 mm. Two strategies for simulating the reaming process are compared. The first one is similar to the one implemented in Achard’s work [21]: all the elements of the reaming area are deactivated in the same calculation step. This modeling strategy allows to obtain the final residual stress state after reaming, it will be called “global reaming” in this study. The second strategy consists in deactivating the elements by several steps along the height of the part in order to simulate the progressive feed of the tool during reaming. 19 calculation steps, each corresponding to the deactivation of around ten elements in the thickness are carried out (Figure 3). This allows obtaining the history of the stress state in the part during reaming. This will be called “progressive reaming”.

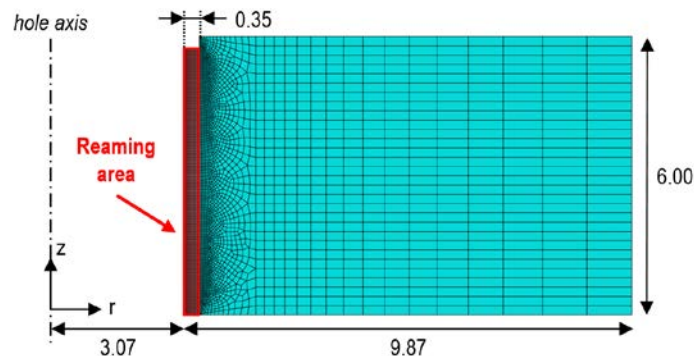


Fig. 3. Representation of the reaming area and the deactivated elements in the first calculation step for the progressive reaming (dimensions in mm)

Thus, the two modelling strategies do not take into account the thermal effects occurring during reaming. The aim is to study only the impact of material removal on the stress state of the part which cannot be studied separately experimentally.

Both modelling strategies should provide similar results. In the case of progressive reaming, the machining kinetics is exploited to define the calculation steps (height of deactivated elements and step duration). This time effect will fully make sense when another model involving progressive thermal loading will be implemented.

2.4. ABAQUS MODEL

The mesh, presented in Figure 4, is refined and composed of biquadratic elements with eight nodes (CAX8) in the areas of high plasticity (sleeve and hole edge area of the part). These elements which imply stress and strain calculations at 8 integration points per element allow providing accurate results that take the plastic phenomena into consideration well. The rest of the workpiece and the jaw are meshed with bilinear elements with four nodes using a reduced integration (CAX4R). These elements which use a reduced integration imply a stress and strain calculation at only one integration point by element. This allows saving computational time without losing accuracy, the areas being slightly plastically deformed.

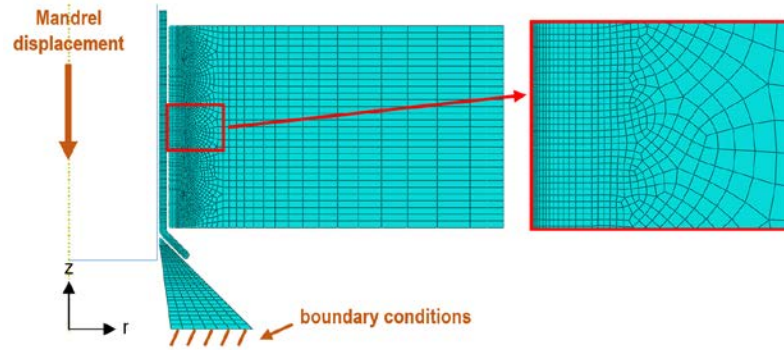


Fig. 4. Mesh of the numerical model

In this study, the effects of inertia are neglected. Hence, the problem is considered quasi-static and is solved with Abaqus/Standard which uses an implicit time integration scheme. With this iterative method, the calculation of the current quantities in one time step are based on the quantities calculated in the previous time step (1). The advantage of this integration scheme is that even if large time steps are taken, the solution remains stable. However, the disadvantage is that it requires the calculation of the inverse of the non-diagonal stiffness matrix which can be time consuming [26].

$$\Delta u^{(i+1)} = \Delta u^{(i)} + K_t^{-1} \cdot (F^{(i)} - I^{(i)})$$

Δu : increment of displacement
 K_t : current tangent stiffness matrix
 F : applied load vector
 I : internal force vector

3. RESULTS

During cold expansion simulation, residual stresses are generated in the part along the three directions: axial, radial and circumferential.

Figure 5 shows the stress states in the part for the three directions after cold expansion and global and progressive reaming simulations.

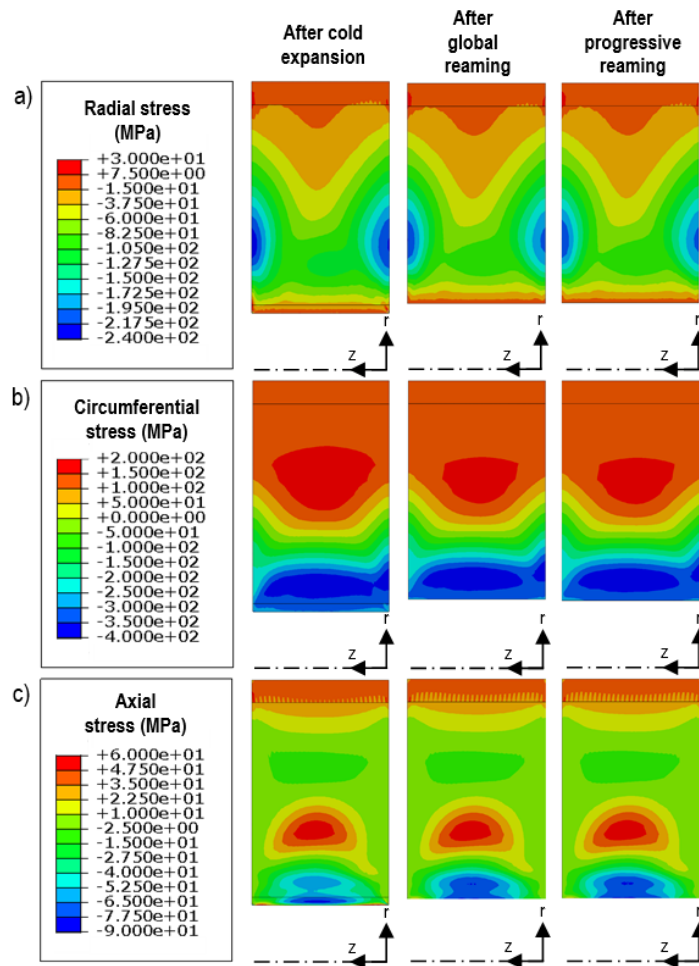


Fig. 5. Radial (a), circumferential (b) and axial (c) stress states obtained in the part at the end of the cold expansion (1st column), global (2nd column) and progressive (3rd column) reaming simulations

These results show a non-homogeneous distribution of the residual stresses in the part after the cold expansion and reaming processes. The method for deactivating the elements in order to simulate the reaming process does not seem to affect the final stress state of the part.

Axial residual stresses are largely lower than radial and circumferential stresses. Hence, the rest of the study focuses on the latter two.

The low influence of the reaming simulation on the residual stress state of the part can be noted. The radial residual stress field undergoes a progressive offset in the radial direction during the reaming simulation. The two compression points on the entry and exit faces are slightly relaxed and the radial residual stress tends to homogenize in the thickness of the part. This relaxation could be related to the reduction of the axial strain at the hole edge on the entry and exit faces which is generated during the cold expansion process and which is sometimes called “volcano effect”. Concerning the circumferential residual stress field, this one is simply truncated in the reaming area. Thus, a higher compressive stress state favoring a longer fatigue life is obtained at the hole edge.

The radial and circumferential residual stresses on the entry face and middle section of the part after cold expansion, global and progressive reaming simulations are shown in Figure 6. Radial stresses are compressive and have a characteristic profile. They cancel at the hole edge and at the free outer edge of the part. Circumferential stresses are of mixed nature with a compressive peak at the hole edge and then a tensile zone far from the hole.

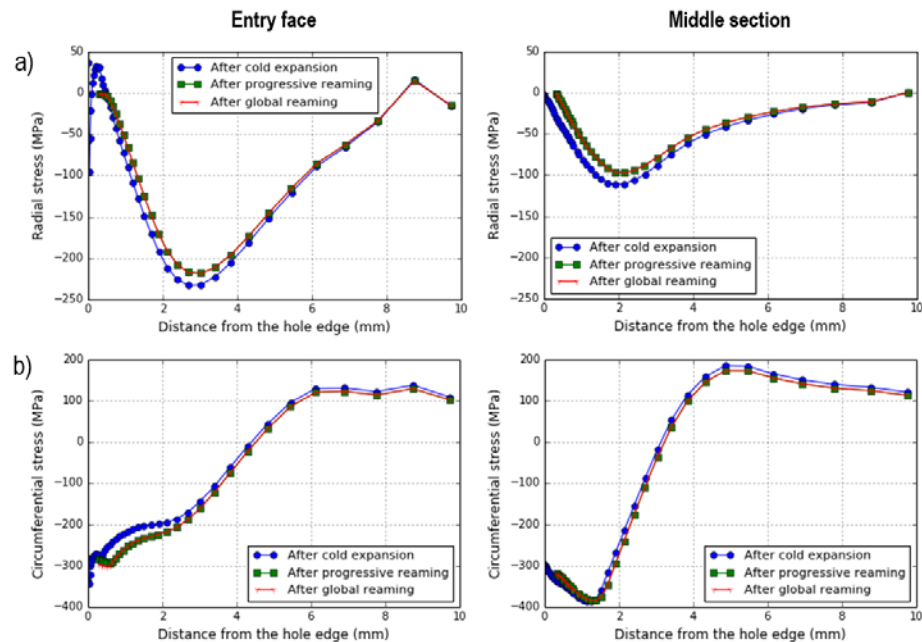


Fig. 6. Evolution of radial (a) and circumferential (b) residual stresses along the entry face (1st column) and middle section (2nd column) of the part after cold expansion and global and progressive reaming simulations

A relaxation of the radial residual stress is observed during reaming simulation with a 7 % reduction in the compressive peak on the entry face and 15 % on the middle section. The modification of the circumferential residual stress is significant only on the entry face with a 6 % increase and a small offset of the compressive peak. Even though the level of residual stress changes during the reaming simulation, the heterogeneity of the stress state in the part remains. Indeed, the residual stress curves obtained after the cold expansion and reaming simulations present similar shapes. The changes in residual stress states are located in the hole edge area.

The final results obtained with the two simulation strategies for reaming are identical. This confirms the equivalence of the two methods to obtain the residual stress state of the part at the end of the reaming process. The progressive reaming method seems nevertheless more interesting because it allows accessing to the intermediate stress states during the process.

The evolution of the residual stress fields during progressive reaming is studied in order to better understand the impact of the process on the material characteristics of the part. For this purpose, radial and circumferential stresses are measured on 9 elements distributed according to the height and depth of the part. The location of these elements is described in Figure 7.

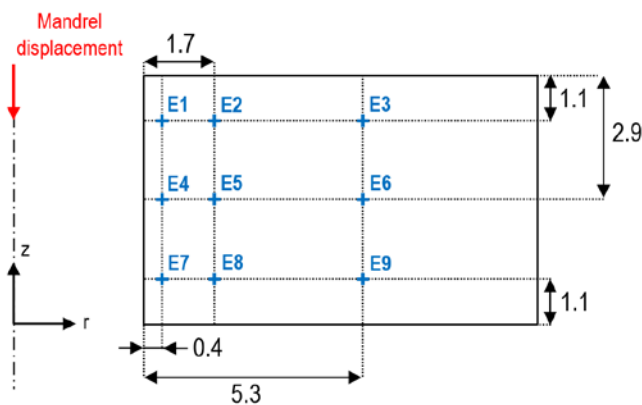


Fig. 7. Selected elements locating (center) in mm on the part after cold expansion simulation for constraint results reporting

The residual stress evolution for each element is presented in Figure 8. On these graphs, a dotted line indicates the position of the elements where the stress results are measured in relation to the part depth.

The evolutions of the residual stress during the reaming process present different shapes depending on the elements considered. A stress balancing takes place gradually when the elements bands are deactivated for the elements located at the same level in the part thickness. This balancing is mainly carried out in the radial direction and intensifies by approaching the hole edge. Indeed, the elements located exactly at the hole edge (E1, E4 and E7) show a sudden stress

evolution. The elements a little farther away from the hole edge (E2, E5 and E8) present a smoother evolution. Finally, the elements very far from the hole edge (E3, E6 and E9) show almost linear evolutions.

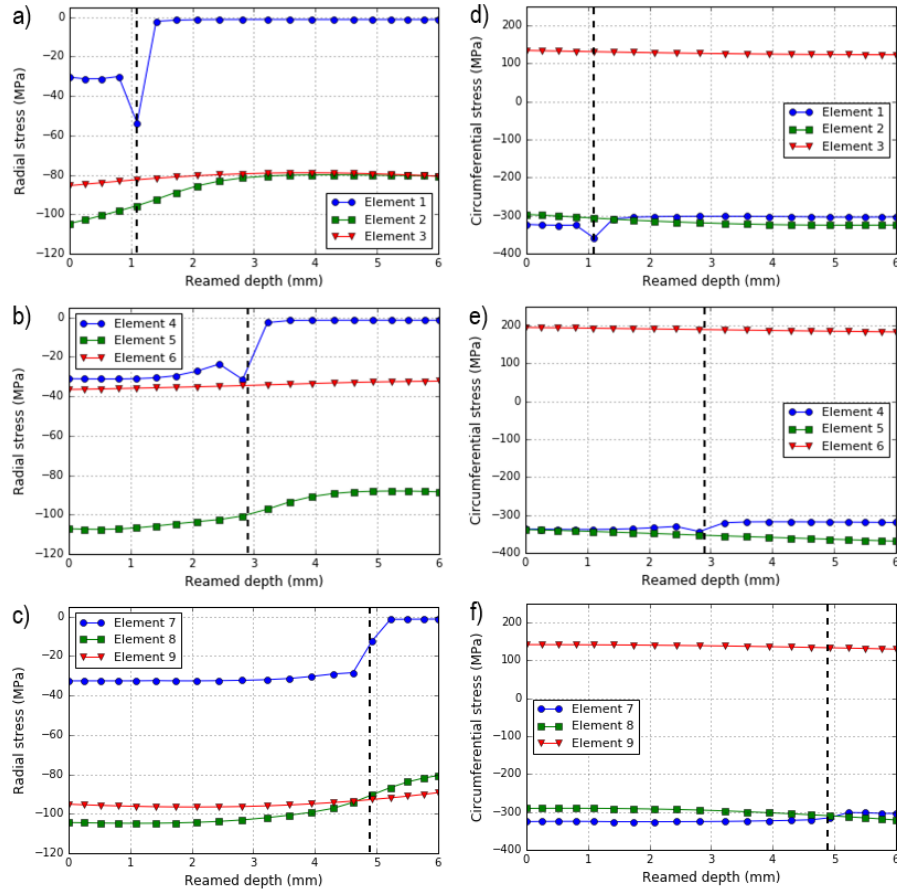


Fig. 8. Evolution of radial (a,b,c) and circumferential (d,e,f) residual stresses during progressive reaming simulation

4 DISCUSSION

The comparison of the numerical results obtained with experimental results is not yet possible. Indeed, it is impossible to implement experimentally the mechanism of material removal without involving thermal phenomena. Therefore, the results obtained are compared with previous numerical work as a first validation step.

Kang [27] in his work develop a 3D FEM simulating the entire cold expansion process including hole expansion, recovery and finish reaming. A quarter of 2024-T351 aluminum part is modeled with a thickness of 6.35 mm and a final diameter hole of 7.26 mm. The reaming is simulated through the deactivation of mesh elements in the same way as in this study. Kang provides results of circumferential residual stress along the entry face and the middle section. The result curves present a general shape similar to the one obtained in this study with a compressive peak at the hole edge and a tensile zone far from the hole. However, the shape of the compressive peak varies. This can be explained by the number of points considered for the plotting of the result graphs which depends on the mesh size. The residual stress levels obtained by Kang are of the same order of magnitude as those presented in this study. The differences may be due to the different dimensions used.

Thus, the model developed in this study seems relevant and seems more interesting to gain in computing time compared to the 3D model.

In addition to saving computing time, the interest of the developed model with the progressive reaming method compared to the models of the literature performing the deactivation of the mesh elements in a single calculation step [21,22,27] is the access to the intermediate stress states during the reaming process. The numerical study of the evolution of the residual stress in the workpiece due to the material removal during the reaming process shows a gradual stress balancing as the mesh elements are deactivated along the thickness of the part. In practise during the reaming process, material removal is associated with thermal phenomena that some authors try to quantify [28] and which are not yet taken into account in our model. In order to envisage a more realistic simulation of the reaming process, it would be interesting to consider the intermediate stress states obtained and to gradually apply an equivalent thermal load.

5 CONCLUSION

An enhancement in the reaming simulation is proposed compared to Achard's simulation strategy [21]. This new simulation which consists of progressively deactivating mesh elements allows to access to the history of the residual stress state of the part.

The results obtained show only a small change in the residual stress state of the part during the reaming simulation. It means the material removal has a weak influence on the residual stress state of the part. Thus, if a significant change in the residual stress state occurs during the reaming process, it should mainly be related to the thermo-mechanical phenomena. Therefore, a new strategy of reaming simulation according to the principle of applying a thermo-mechanical load as in Valiorgue's works [20] is envisaged in order to take into account the mechanical cutting and thermal heating phenomena.

Nevertheless, the interpretation of the results emphasize a certain change of the residual stress state in the part during the reaming simulation especially at the hole edge area. It means to envisage a more realistic reaming simulation by applying an equivalent thermo-mechanical load on the hole edge, this one should not be dissociated from the material removal. Thereby, in the envisaged reaming simulation, the loading and the material removal will be applied synchronously and gradually in order to achieve an accurate final stress state in the part.

A reaming simulation on a pre-stressed part obtained after drilling simulation is also envisaged in order to study the evolution of the residual stress state in the hole edge zone during the whole machining process of the hole.

Finally, following this numerical study, an experimental study is envisaged in collaboration with Airbus in order to correlate the numerical results with the experimental measurements. Reaming tests will be performed with residual stress measurements in the part using the X-ray diffraction method and the incremental hole drilling method.

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