Reliable Manufacturing Process in Turbine Blisks and Compressors

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RESUMEN

El negocio de la industria aeronáutica es un sector en continuo crecimiento y la fabricación de componentes aeroespaciales es sin ninguna duda un proceso de alto valor añadido. Cada parte de la aeronave y en particular los elementos que conforman el motor representan algunos de los elementos más costosos debido al complejo proceso de fabricación de su complicada geometría. En este caso, la pieza test para llevar a cabo el estudio es un Blisk. El tiempo de fabricación previsto para este tipo de piezas es elevado, de modo que cualquier mejora en lo referente al proceso de fabricación supone un ahorro considerable. Dada la responsabilidad de este tipo de piezas, no se permite la aparición de ningún tipo de defectos comunes, como marcas de chatter originados durante el proceso de fabricación, lo que reduciría la vida útil de la pieza. En este artículo, considerando la existente demanda de mejores procesos de fabricación, se desarrolla un caso de estudio basado en las operaciones de acabado de un Blisk de Inconel 718. Se desarrolla un modelo estático para la predicción de fuerzas de mecanizado para finalmente validar lo con las fuerzas reales medidas durante el proceso real de mecanizado de la pieza.

Palabras clave: Blisk; Blade; Forces; Ball end-mill cutter.

ABSTRACT

Aeronautics is a business in a continuous growing sector and aircraft manufacturing is without any doubt a high-priced process. Each part of the aircraft and particularly engine parts represent the most expensive elements due to the difficulty of manufacturing their complex geometry. In this case, the test piece to carry out the study has been the Blisk. The predicted lead time for one of these components is so long that any progress related to the manufacturing process implies a considerable amount of saving. Due to the critical nature of the parts common defects such as chatter marks, smearings or pickups originated during the manufacturing process that will reduce the part life are not allowed. In this article, considering the existing demand of better manufacturing technologies a study case based on an Inconel 718 Blisk finishing operations study is developed. A static model for machining forces prediction is developed to finally validate it with the real machining forces measured during the machining process.

Keywords: Blisk; Blade; Forces; Ball end-mill cutter.

1. Introducción

Global air traffic level predictions foretell a fast continuous growth, expecting the number of planes to grow at an average of more than three percent by 2030 [1, 2]. The increasing of the aviation industry represents a challenge in aero engine manufacturing, demanding robust manufacturing and cost efficient solutions ensured by a high level of process control of the machining processes [3]. Therefore, the searching of reliable manufacturing processes for these engine components such as blisks and impellers requires the production of these high added value components to be strictly validated by cutting forces models.

These complex surface parts manufacturing are subject to roughing and finishing operations, being these lasts the ones in charge of sculpting the final part geometry. Finishing operations of complex
geometries and high added value parts manufacturing key step is the CAM programming where a serial of machining parameters such as the tool geometry, the machining type, cutting paths and strategies

Nomenclature

| Symbol      | Description                                                                 |
|-------------|-----------------------------------------------------------------------------|
| D, R, Rr, Rz | Parametric radial dimensions of end mill                                    |
| α, β        | Parametric angles of end mill                                               |
| h           | Valid cutting edge height from tool tip                                     |
| r(z)        | Radial coordinate of a cutting edge point                                  |
| \tilde{r}(z)| Vector from tool centre to cutting edge                                     |
| Mr, Nr      | Radial offsets of the end mill profile                                      |
| Mz, Nz      | Axial offsets of the end mill profile                                       |
| Ψ(z)        | Cutting edge position angle at level z on the XY plane                      |
| ϕj(z)       | Total angular rotation of flute j at level z on the XY plane                |
| ϕ           | Rotation angle of cutting edge                                              |
| i(z)        | Helix angle                                                                |
| Kt, Kr, Ke  | Cutting force coefficients in tangential, radial and axial direction        |
| Kc, Kt, Ke  | Edge force coefficients in tangential, radial and axial direction           |
| dFx, dFy, dFz | Force components in X, Y and Z directions.                                  |

and feed and speed conditions. For this purpose, cutting efforts represent an objective criterion to be used for machining strategies selection [4]; the lower the value of the forces, the better the machining strategies will be [5]. Cutting forces are responsible for many events taking place during the manufacturing process [6]; some of these events could be errors due to tool flexion, tool wear or thermal effects. The cutting forces value should be maintained in an optimal range to avoid severe errors in the mentioned events.

Taper ball-end mill cutters play an important role in the machining of complex surfaces of high added value parts. Therefore, evaluating the profile of this type of cutter is very important [7]. Mechanic and dynamic models individually developed for face, cylindrical, ball end and taper ball end mills have been reported in classical literature approaches [8-10]. These models shape the geometry of each cutter, the chip load distribution along the cutting edges and mechanistically obtain the cutting coefficients required to predict forces [11]. A generalised mechanistic and dynamic model is therefore required in order to analyze finishing operations of blisks blades with taper ball-end mill cutters for robust manufacturing solutions.

The mechanistic model, derived from Lee and Altintas [12], introduces as input parameters the cutting parameters including the tool geometry, the part material, and the cutting conditions; this is feed, speed and axial and radial depth. The model is based on infinitesimal discretization of the tool edge. This way a simplified cutting forces model is applied to each discretization element. Thus, the addition of each infinitesimal element efforts will determine the total efforts amount of each tool edge. After that, once the number of tool edges simultaneously involved in each tool inmersión, the total force acting on the tool will be calculated.

In this paper, a static model for machining forces prediction is developed to finally validate it with the real machining forces measured during the machining process of a study case based on an Inconel 718 Blisk manufacturing strategies.
2. Forces prediction model for taper ball-end mill cutters

The developed model, applicable to cutting forces calculation, introduces cutting parameters as input data. They include information related to the tool geometry, part material, and cutting conditions such as feed, speed and radial and axial depth.

The model is based on the tool edge discretization into different infinitesimal elements in order to apply a simplified model of the cutting force to each element. Therefore, the combination of each infinitesimal element results and posterior addition of the edge total efforts will determine the total the total force applied on the tool.

The resulting force components on the tool are obtained after projecting the strength of each discrete element edge on a common reference system and posterior integration along the tool edge. For each discrete edge element the three infinitesimal components of the cutting forces are calculated. These components are tangent force, radial force and the binormal force component, which is normal to the plane including the two other components as seen in Figure 1. The tool division into infinitesimal elements is made by successive sections of parallel to XY planes. The angular position of each differential element is defined by the turned angle $\psi$.

![Figure 1. Tangential, radial and binormal forces.](image)

In the considered model, the forces are supposed to be caused by two different physical phenomena. On one hand, the shear caused force that is inherent to the cutting formation process, and on the other hand the friction caused by the sliding edge over the surface being machined. Taking all these concepts into account the cutting force is reduced to the following expression (Ec.1.).

\[
\begin{align*}
    dF_t(\theta, z) &= K_{tc}dS + K_{tc} \cdot t_n(\Psi, \theta, \kappa)db \\
    dF_r(\theta, z) &= K_{rc}dS + K_{rc} \cdot t_n(\Psi, \theta, \kappa)db \\
    dF_a(\theta, z) &= K_{ac}dS + K_{ac} \cdot t_n(\Psi, \theta, \kappa)db
\end{align*}
\]  

(1)

Where,

$t_n(\Psi, \theta, \kappa)$, is the undeformed chip thickness normal to the cutting edge. It is measured in millimeters and varies depending on the angular position on the edge differential element.

$dS$, is the tool differential element length in millimeters.

The specific friction cutting coefficients $(K_{tc}, K_{rc}, K_{ac})$ represent the effort per millimeter made by the cutting edge in tangential, normal and binormal directions. These friction efforts are measured in N/mm.
The shear specific coefficients \((K_{tc}, K_{tr}, K_{tc})\) represent the necessary cutting force for a chip thickness square millimeter shearing in each direction mentioned. They are measured in N/mm.

For cutting forces equation resolution it is necessary to obtain the chip thickness and the tool edge length values. These parameter values depend on the tool geometry and on the cutting parameters, thus, the first step is based on the tool geometry model to subsequently obtain \(r_n(\Psi, \Theta, \kappa)\) and \(dS\) values. These calculations require a serial of stages as seen in Figure 2.

The first one is the calculation of the empirical coefficients in charge of the material characterization. An initial experimental measure of the cutting forces is obtained during a serial of machining trials oriented to this purpose. Afterwards, once the empirical coefficients are obtained, the geometric modelization of the tool edges is carried out. In this step, \(x, y\) and \(z\) tool edge positions, the undeformed tool cheap section, the tool chip thickness and the length of each discrete tool element is obtained. Finally, each differential element cutting forces are calculated and Ec. 1 is applied. Por último, se integran las fuerzas calculadas en el paso anterior a lo largo del filo, obteniéndose así los valores de fuerzas de corte resultantes. Finally, forces calculated in the previous step along the edge are integrated and the resultant cutting forces values are obtained.

![Figure 2. Proposed steps for cutting forces](image)

3. Geometric model of tool edges and chip thickness

Once it is time to carry out the integration along the tool edge, it is necessary to know \(dS\) and \(\psi(z)\) values. These parameter values depend on the tool geometry and are going to be obtained for the taper ball-end mill cutter. The most characteristic parameters of this tool are the ones shown in Figure 3.

![Figure 3. Tool geometry and Principal angles of a taper ball-end mill cutter](image)

3.1. Helix and lag angle

Ball taper-end mills are formed by a conical feature (NS arc) with a constant helix angle \(i(z)\) and a spherical feature (MN arc) with a variable helix angle. The helix angle \(\psi(z)\) has a different expression for each zone along the flute, which is wrapped around the general cutter geometry.

Because of the changing radial offset from the cutter axis, the helix angle for MN arc varies along the flute for constant lead cutters as,

\[
i(z) = \tan^{-1}\left(\frac{(r(z) - Rr) \tan \Theta_0}{R}\right) \tag{2}
\]

Owing the spherical area of the tool does not conform a full quarter due to the tangency to the cone, there is a discontinuity at point M and therefore the lag angle expression is,

\[
\psi(z) = \frac{(R + z - Rz) \tan \Theta_0}{R} \tag{3}
\]
The taper zone of the studied taper ball-end mill does have constant helix angle along the flute.

The helix angle for NS arc is constant,

\[ i(z) = io \]  

And the lag angle changes along the flute for NS arc.

\[ \psi(z) = \frac{\ln(Nz-(Nz-z) \tan \beta)}{\sin \beta} \cdot \tan io - \psi2s + \psi ae \]  

The final lag angles at the end point N of the arc are \( \psi ae \) and \( \psi2s \).

### 3.2. Edge points position

The \( \vec{r}(z) \) vector (Figure X) defines the elements as part of a cutting edge \( j \) depending on their angular position \( j \), the radius \( r(z) \) and the height \( z \):

\[ \vec{r}j = r(\phi j) \cdot (\sin \phi j \cdot \vec{i} + \cos \phi j \cdot \vec{j}) + z(\phi j) \cdot \vec{k} \]  

### 3.3. Radius and axial tool position angle variation along the tool edge

In a taper ball-end mill both the radius and the position angle vary.

The radial offset at elevation \( z \) and the tool position angle variation for the two different areas are:

**MN arc (spherical area)**

\[ r(z) = Rr + \sqrt{R^2 - (Rz - z(\psi))^2} \]

\[ \kappa(z) = \sin^{-1} \left( \frac{r(z)-Rr}{R} \right) \]  

**NS arc (tapered area)**

\[ r(z) = Nr + (z(\psi) - Nz) \cdot \tan \beta \]

\[ \kappa(z) = \frac{\pi}{2} - \beta \]  

### 3.4. Edge length differential element \( dS \)

An edge length differential element \( dS \) of a helical cutting edge segment can be given as follows:

\[ dS = \frac{d\phi}{d\phi} = \vec{i}(r'(z) \sin \phi j + r(z) \cos \phi j) + \vec{j}(r'(z) \cos \phi j \cdot \phi' j - r(z) \sin \phi j \cdot \phi' j) + \vec{k}(z') \]  

\[ dS(\phi) = |d\phi| = \sqrt{r''(\phi) + (r'(\phi))^2 + (z'(\phi))^2} \]  

Where,

\[ r'(\phi) = \frac{dr(\phi)}{d\phi} \]

\[ z'(\phi) = \frac{dz(\phi)}{d\phi} \]  

### 4. Model validation

The predicted forces obtained for the cutting conditions detailed in Figure 4, can be compared to the real machining measurement [13]. The forces were measured using a Kistler® 9255B table in a machining centre Ibarma® ZV25/U600. The cutting forces were measured by machining monitoring during the machining processes for the machining strategy.
Figure 4. Cutting forces comparison between real measured forces and model predicted forces

5. Typical ball-end mill machining operations

Blade surfaces are one of the most characteristic examples of taper ball-end mills use as seen in Figure 5. They are mainly present for flank milling of complex surfaces. These kinds of surfaces tend to suffer from deformation and chatter problems. Establishing an admissible strategy with forces values control, enables the calculation of the cutting forces that are going to be tolerated during the machining process, defining the adequate process parameters.

Figure 5. Typical ball-end mill machining operations.

6. Conclusions

A forces prediction model for taper ball-end mill cutters is presented in this article. For the given tool geometry and workpiece material, the experimental results show that there is a correspondence between the predicted forces and real measured forces.

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