A Study of Progressive Milling Technology on Surface Topography and Fatigue Properties of the High Strength Aluminum Alloy 7475-T7351

Miroslav Piska, Petra Ohnistova, Jana Hornikova and Charles Hervoches

Introduction

Machining process in aerospace industry is often characterized by high material removal up to 95%. Many of the primary and secondary aircraft structures such us spars and ribs have to be lightened by milling operations because of the strict weight reduction requirements and according the trend in design preferring the monolithic parts to the assembled parts. However, during machining process, the surface layer of the component is subjected to elastic-plastic deformation and heating, what result in different thickness of the machined walls, residual stresses, strain hardening, structural changes and surface topography changes which are having important impact on the fatigue properties, esp. in thin-walled parts [1–3].

It is well known that fatigue life and tensile strength are highly dependent on the final surface quality because the micro-cracks are usually initiated on the free surfaces where the stress concentrations are the highest [4], what can be observed in cyclic loading. Consequently, a set-up of some inappropriate cutting conditions may affect the surface quality and related fatigue properties of the machined components. In aircraft industry the need for optimal cutting conditions should be selected correctly with respect to the fatigue properties of the machined and exposed parts.

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Several studies have been already focused on the effect of cutting conditions on the surface quality and related fatigue life. For example, Sasahara [5] in his paper presents the effect of residual stresses and surface hardness on the fatigue life of the steel (0.45%C) resulting from different cutting conditions of turning. Suraratchaï [6] studied the influence of the surface integrity on the fatigue performance of an aeronautical aluminum alloy 7010-T74511 while using different cutting conditions of the face milling. Gómez [7] studied an influence of cutting conditions of the turning process on the fatigue performance of the aluminum alloy A92024-T351. Sunday [1] presented a study of the influence of machining parameters on the fatigue life of end milled aluminum alloy 2024. However, the effect of the cutting conditions of shoulder milling strategy on the surface quality and related fatigue life of thin walled components has not been fully examined in the previous studies, so this presents a contribution the problematic.

Theory of Milling

Chip Formation During Shoulder Milling

During shoulder milling operation, the cutting is accomplished by a peripheral flute of a cutter and the rotational axis of the cutter is always parallel to the machined surface. Chip formation is therefore performed by the peripheral cutter and is variable in time and over the position at the cutting edge. Chip cross section can be derived from the analysis of the helical conoid and can be determined for each flute (tooth) and its geometry. During shoulder milling operation, the motion of the tooth and associated variation of the chip cross section area at each point can be observed. Together with the time change the specific cutting forces, the total loading of the workpiece surface and related cutting performances vary [8].

Force Loading of the Shoulder Milling

Determination of the force loading during shoulder milling operations can be predicted theoretically and verified experimentally. All theoretical calculations are based on the specification of the chip cross section which corresponds to the analysis of a helical conoid and specific cutting forces [8]. Force loading of the milling cutter can be therefore defined as an indefinite integral with the hypergeometric function (1, 2) including a material constants $\underline{c_0}$, $\underline{mc}$ and angle of engagement $\underline{\varphi}$:

$$F_c = \int_{\varphi_1}^{\varphi_2} dF_c = c_o. \int_{\varphi_1}^{\varphi_2} \sin^{1-mc}\varphi \, . \, d\varphi. \quad (1)$$

The cutting force can be used for calculation of the specific cutting energy kc:

$$k_c = F_c/A_D = (c_o/(a_p.a_e)). \int_{\varphi_1}^{\varphi_2} \sin^{1-mc}\varphi \, . \, d\varphi, \quad (2)$$

where A_D is the un-deformed chip cross-section, a_p and a_e the axial and radial depths of cut. Workpiece loading and its deflection, however, depends not only on cutting force F_c mentioned above but also on the force perpendicular to the cutting force that is acting in the radial direction to the cutting tool. This force is known as F_{cN} and its prediction is difficult because of its dependency on the macro and micro geometry of the tool, tribology of the interface tool-chip-workpiece and on the tool wear. Its magnitude and orientation vary significantly with the tool wear similarly as the orthogonal passive force F_p [8].

For these reasons, the experimental measurement of the instantaneous force loading corresponding to the maximal chip cross section is inevitable. Precise analyses of the force loading make the base for specific cutting energy calculations which are dominant for presence of residual stresses after machining.

Surface Quality After Machining

Machining process is determining for the final state of the workpiece surface [9]. Surface morphology after a machining operation contributes to the surface integrity which integrates several different aspects such as surface topography, surface microstructure, mechanical properties, residual stresses, corrosion resistance and life of a part [10].

Surface topography is defined by the 2D and 3D parameters [11]. The two dimensional parameters are further divided into many roughness amplitude parameters such as for example Rq, Rt, Rz, Rp and Rv, waviness parameters such as Wa, Wq, Wt and Wz and into the parameters defined by the Abbot-Firestone curve (specifying the percentage of the material of the profile elements at a defined height level relative to the evaluation length). Analysis of this curve is significant mainly for a prediction of initial wear, a wear evolution during operation or the ability to retain liquids in the operational use [12, 13].

In various publications, the average surface roughness Ra was used to evaluate the influence of surface topography on the fatigue life [14, 15]. However relatively large variance in fatigue results have been observed. With booming use of optical or other advanced measuring devices the other surface parameters are subjects of studies frequently.

Residual Stresses After Machining

The stresses imposed by the elastic-plastic deformation, heat treatment, strain hardening or even heat softening during mechanical processing of the raw material are commonly known as residual stresses [16]. These stresses vary in depth, magnitude and orientation and can have a very significant effect on the fatigue properties of the machined component. These stresses can be tensile or compressive and the stressed layers vary in depth according to the used cutting conditions, work material, tool macro and micro geometry and other conditions of the interface tool-chip [17]. Compressive residual stresses are usually beneficial at the free surface and they decrease with increasing depth. Compressive stresses generally improve fatigue performance of the machined component because in some case prevent fatigue crack nucleation or slow down its propagation. Further increase in the depth results frequently in the tensile residual stresses which accelerate the degradation and fracture damage [18, 19].

Experimental

Material of Workpiece

Aluminum alloy 7475-T7351 was selected as a workpiece material because of its real use in aerospace industry today especially for structural parts which are subjected to the cyclic loading during flight. The aluminum alloy 7475 is an alloy with the so-called controlled toughness, developed by the producer ALCOA, providing a combination of high strength, good fracture toughness and high resistance to the fatigue crack propagation—Tables 1 and 2. The alloy 7475 is a refinement of the alloy 7075 and its fracture toughness for plates are almost 40% greater than for the previous version 7075 at the same temperature. The prevalence in some properties is a result of the reduction of the Fe, Si and Mg contents and is as influenced by thermo-mechanical and heat treatments procedures. The material 7475 is recommended when a high fracture toughness of a part (typically the aircraft wings or wing spars) are considered. The application of T7351 heat treatment provides also optimal resistance to the stress corrosion cracking [20].

Cutting Tools, Machine

The SECO end-milling tool ∅ 16 × 55 × 115 JS513160D3C.0Z3-NXT (SMG N11, (Ti,Al)N coating) for the thin-wall machining was used. Tool micro-geometry was analyzed with Alicona Edge Master/ALICONA-IF G4. The cutting experiments

Table 1 Chemical composition of 7475-T7351 [20]

Element	Weight content (%)
Si	0.10 max.
Fe	0.12 max.
Cu	1.20–1.90
Mn	0.06 max.
Mg	1.90–2.60
Cr	0.18–0.25
Zn	5.20–6.20%
Ti	0.06 max.
Others, each	0.05 max.
Al	Balance

Table 2 Mechanical properties of 7475-T7351 [20]

Thickness of the sheet (mm)	25–38	50–63	75–89
Tensile strength (MPa)	490	476	448
Yield strength (MPa)	414	393	365
Elongation (%)	9	8	8

were carried out at the 5-axis milling center MCV 1210/Sinumerik 840D. Cutting experiments were performed for various cutting speeds and feeds—Fig. 1.

Force Loading Measurement

The force loading during milling was measured with the stationary KISTLER 9575B/SW and analysed with SW DynoWare. Mean values of the maximal instantaneous force loadings in X, Y and Z direction for determination of the resultant force F_{1M} and its decomposition to the force loadings F_c and F_{cN} and calculation of specific variables for up and down milling.

Surface Topography Measurement

A very complex measurement of the surface topography was performed on the rigid samples using high resolution optical device ALICONA-IF G4. A single measurement contained 30 million of data giving information about 2D and 3D parameters of the scanned surface of 5×5 mm^2. Surface topography was measured in two directions X and Y corresponding to the coordinate system of the measurement device ALICONA-IF G4. Axis X corresponded to the direction of the tool axis, direction Y is perpendicular to the previous and corresponds to the direction of the tool movement. Measured values were processed using of one-way analysis ANOVA.

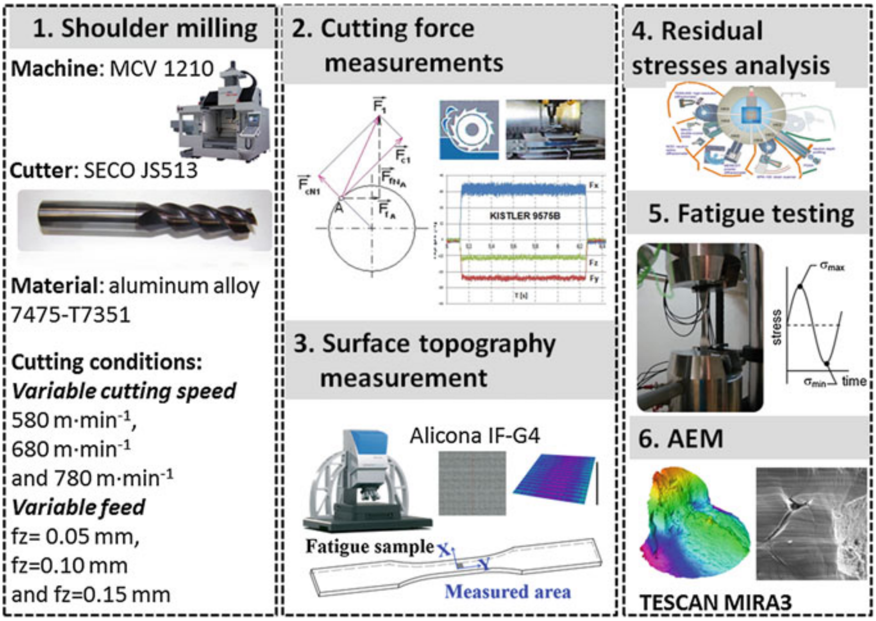

Fig. 1 Experimental set-up of the measurements

Fatigue Testing and Fracture Surface Analysis

First objective of the fatigue testing was to simulate tensile high cycle loading of the thin-walls separating pockets of the wing panels. Second objective was to examine the influence of the cutting conditions of the shoulder milling and corresponding surface quality on the fatigue life based on the S/N curve of un-notched

7475-T7351 plate from MMPDS (Metallic Materials Properties Development and Standardizations) the following specifications and parameters of the fatigue testing were used:

- an axial testing machine BISS,
- the flat un-notched fatigue specimen according to ASTM-E466 and EN 6072 with the minor adjustments of the clamping area of the sample,
- the fluctuating tensile cycle R = 0.1, f = 10 Hz.

In order to examine the influence of the cutting conditions, three series of the specimens according to the cutting conditions (fz = 0.05 mm, fz = 0.10 mm and fz = 0.15 mm), just corresponding with the surface quality were used for every stress level. The electron microscope Tescan MIRA 3 equipped with EDS probes was used to evaluate the source of the crack nucleation (SEM/AEM).

Residual Stresses

Residual stress analysis was performed at Neutron Physics Laboratory of CANAM infrastructure of Nuclear Physics Institute, Řež near Prague, Czech Republic according to the neutron diffraction method [21]. Two-axis diffractometer SPN-100 [22] placed at thermal neutron source (reactor LVR-15, which belongs to Research Centre Řež) was used for mapping of residual strains inside the material 7475-T7351. Principle of the measurement was based on the accurate evaluation of positions of a selected diffraction peak from small material volume defined by a set of input and output slits according to Hutchings [23]—Fig. 2. Positioning of flat specimens in dimensions 370 × 35 × 5 mm was ensured by the six-axis robotic arm allowing more flexible manipulation.

Results and Discussion

For both milling strategies (up and down milling) have been found, that an increase of feed speed resulted in a higher cutting force F_c and higher ratio F_c/F_{cN}. On the other hand, the increase of the cutting speed did not result in a significant growth of the force loading neither of the specific cutting energies (in the tested interval of cutting speeds). However, the down-milling milling strategy for all the experiments is analyzed more in detail here because of its superior results.

Surface topography measurement confirmed that the increase of the feed speed lead to an increase of roughness and waviness parameters. Increase of the feed by three times was followed by increases of the R_a from 0.31 to 0.80 µm (by 158%), R_v from 1.24 to 1.91 µm (by 54%) or W_t from 1.23 to 1.92 µm (by 56%). The effect of the cutting speed on the surface topography wasn't statistically

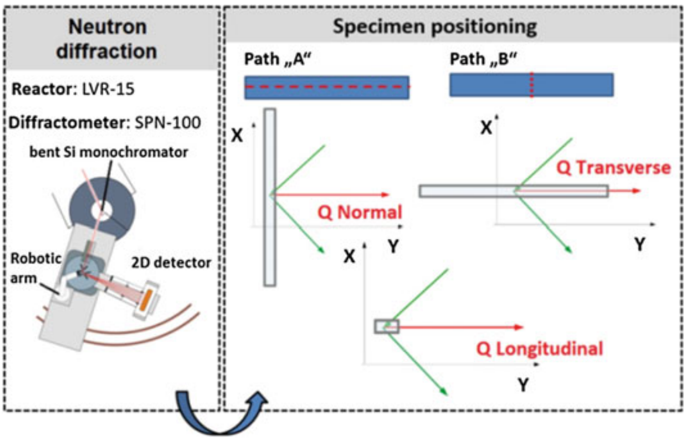

Fig. 2 A scheme of the residual stresses measurement by the thermal neutron diffraction

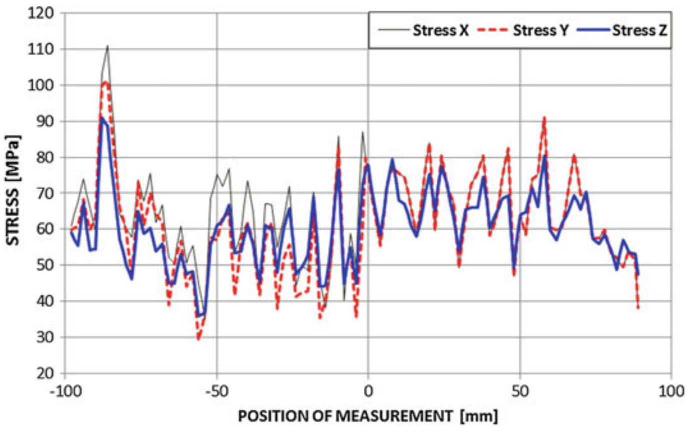

Fig. 3 Residual stresses along the longitudinal axe (Path "A") of a sample. Stress X: *Q Normal*, Stress Y: *Q Transverse*, Stress Z: *Q Longitudinal*

significant ($\alpha = 0.05$) in the tested interval of cutting speeds. The higher Rpk parameter values were observed with increase of the feed speed so more progressive wear of the workpiece surfaces can be expected while using higher feeds. The analysis of the orthogonal residual stresses showed relatively low values of for all tested conditions and measured samples—Fig. 3.

Results of the fatigue testing are presented in the S-N graph (see Fig. 4). The metallographic cross-sections proved that for the defined machining conditions of shoulder milling of aluminum alloy 7475-T7351, the thickness of layer affected by machining was approximately 1 µm and values of the roughness (Ra = 0.815 µm, Rt = 5.34 µm a Rv = 2.06 µm) showed not to be crucial to cause fatigue crack nucleation—Fig. 5.

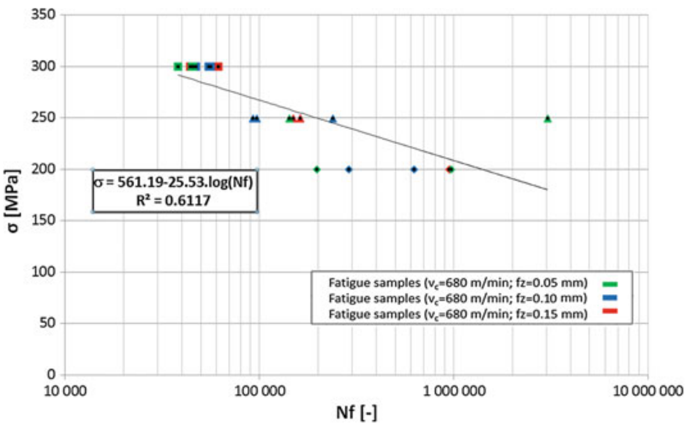

Fig. 4 S-N curve for un-notched machined sample made of aluminum alloy 7475-T7351

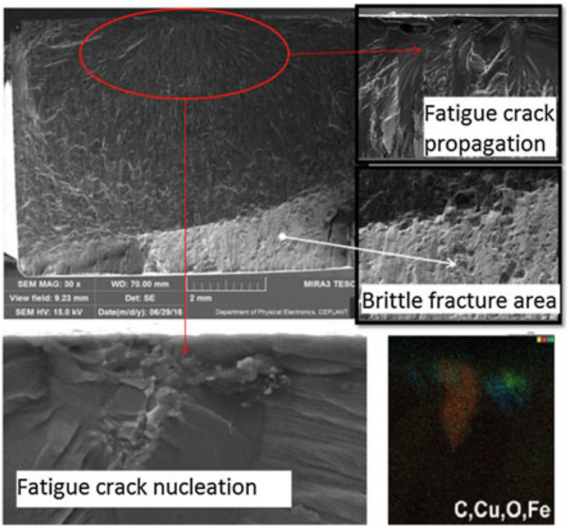

Fig. 5 Fatigue fracture surface analysis

Conclusions

The hard complex inclusions Fe-Cu-C-O were crucial for disturbing the material integrity and production of local stress risers and suppressed the role of surface roughness or selection of cutting conditions in the analyzed ranks. Neither the surface topography nor the imposed specific cutting energies were the key factors affecting the fatigue performance of the machined aluminum alloy 7475-T7351. Fatigue fracture analysis showed that the material inclusions dispersed in the adherent machined surfaces trigger the fatigue crack initiations and propagations. The next research is focused on the analysis of the mechanism in direct SEM tensile test observations and elimination of the material inhomogeneities.

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