Micromilling strategies for machining thin features

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Abstract: Micromilling of metal structures with 'thin' features represents a major challenge towards broadening the use of this technology in a range of microengineering applications, for example in producing multi-channel microstructures, housing for mechanical microdevices, and surgical instruments. The most common thin features seen in microengineering products are ribs and webs.

This research identifies the main factors affecting the reliability of micromilling technology when employed for the machining of microcomponents incorporating thin features. The general principles that should be followed in designing machining strategies for such features are discussed in this article. Taking these general principles into account, new strategies are proposed to reduce the negative effects of identified factors on part quality and, at the same time, to overcome some of the problems associated with the use of conventional machining strategies for micromilling of ribs and webs. To implement and verify them, initially the milling operations were programmed manually, and then a special CAM module was developed for their automatic generation. Finally, this article reports the validation of the proposed strategies for machining thin features, which was carried out on a specially designed test part.

Keywords: micromilling, thin ribs and webs, CAD/CAM

1 INTRODUCTION

There is a growing demand for product miniaturization that requires the development of direct and indirect methods for manufacturing parts and tooling inserts that incorporate thin features. In this research, a thin feature is considered 'a three dimensional body in which one geometric dimension, the thickness, is significantly (more than seven times) smaller than the others' [**1**, **2**].

One of the viable manufacturing routes for producing metal components that incorporate such thin features is their machining from a solid block of material. Especially, it is a promising route for manufacturing complex microengineering structures and thus significantly reducing the complexity of follow-up assembly/integration operations. At 'macro' scale, this could be achieved by assembling the products from thin section components, whereas this is not a viable alternative for their manufacture at 'micro' scale. Micromilling of metal structures with 'thin' features represents a major challenge towards broadening the use of this technology in a range of microengineering applications, for example in producing multi-channels, housing for mechanical microdevices, and surgical instruments.

The most common thin features seen in microengineering products are ribs and webs. When ribs are manufactured employing micromilling, their surfaces are formed by periphery cutting. In contrast to ribs, the web surfaces are machined by end-milling. To develop strategies for reliable micromachining of such thin features requires a systematic investigation of the different factors affecting the quality of the manufactured microstructures.

The main factor preventing the broad use of micromilling for producing microstructures incorporating thin features from a solid block of material is the stability of the machining operation. By making ribs and webs thinner, their stiffness decreases, which could result in the occurrence of vibrations during machining. As a consequence of

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this, the process accuracy deteriorates and could lead to the manufacture of substandard components. The high-frequency vibrations that could occur during micromilling result in poor surface quality. Because of the feature sizes, it is not possible or cost-effective to correct this by follow-up finishing operations.

This article discusses the main factors affecting the reliability of micromilling technology when employed for machining microcomponents incorporating thin features. New strategies are proposed to reduce the effects of these factors on part quality and at the same time to overcome some of the problems associated with the use of conventional machining strategies for milling of microribs and -webs. To implement them initially, the milling operations were programmed manually, and then a special CAM module was developed for their automatic generation. Finally, the proposed strategies for machining thin features were validated on specially designed test part.

2 LITERATURE REVIEW

2.1 Machining of thin features

The main factors affecting the machining of thin features at 'macro' scale are studied by many researchers. Tlusty *et al.* [**3**] identified the main problems associated with the use of long end-mills in high-speed milling of thin features. To increase the reliability of the process, it was proposed that thin ribs be machined by using cutting tools with relieved shank. The machining strategies that should be applied in such cases are a series of axial passes that include roughing and finishing or not finishing at all in each pass. Unfortunately, such an approach cannot be applied in micromachining because cutting tools with diameter $<300\ \mu m$ are used.

Rao [**4**] proposes a method for machining thin webs that are supported either by positioning them directly against the table of the machine tool or by using specially designed fixtures. Thus, the stiffness of the webs would be much higher in the direction of the axial cutting forces. Fairman [**5**] studied experimentally the main factors contributing to the occurrence of vibrations during the machining of thin features. In particular, the effects of axial and radial depths of cut, the spindle speed, and tool geometry were investigated.

Other researchers have proposed models for simulating the effects of different factors on machining conditions during milling of thin features. For example, Kline *et al.* [**6**] proposed using the plate and beam static theory to develop a finite element analysis (FEA) model of the end-milling process. Altintas *et al.* [**7**] developed a dynamic model for simulating a peripheral milling of very flexible plate type structures.

In addition, researchers have proposed some general principles that should be followed when designing parts incorporating thin features. In particular, the design should allow such features to be supported by their adjacent features/structures during the machining. The technique developed by Tlusty *et al.* [**1**] for machining thin ribs essentially uses the stiff, uncut portion of the workpiece to support the flexible section being cut. This general principle can also be applied to thin webs; however, there is a major difference in the orientation of the supporting structures in respect to the cutting tool. When machining ribs, the support structures should increase the part stiffness in a direction radial to the cutter. In contrast, for machining webs, the part stiffness along the tool axis should be increased.

2.2 General issues in micro-end-milling

Micro-end-milling operations could be considered as just one type of conventional end-milling operations, if special attention is not paid to the sizes of the cutters used during machining [**8**]. In particular, the ratios between feed rates per tooth (f_t) and tool radius (r) are selected much higher in micromilling operations to maintain relatively higher removal rates. As a consequence of this, the stresses on microcutters increase significantly in comparison with those in 'conventional' milling and thus the tool life is reduced drastically. Some researchers reported 100 in of tool life when hard metals are machined [**8**].

The most important factors affecting the tool life in micromilling are those related to the selected cutting conditions. In the case of conventional milling, machine operators judge the cutting tool conditions by monitoring the process visually and/or looking for changes in its acoustic 'profile'. Unfortunately, they cannot detect visually the breakages of the cutters due to their small sizes and the generated chips and cooling mist in the machining area. In addition, the acoustic 'fingerprint' of the process and the high-frequency vibration generated by it are such that it is not possible to distinguish any changes from the background noise in the case of a tool failure. Thus, the operator is not able to tune micromilling operations by just monitoring the cutting process and as a consequence of this, hours of machining time could be wasted if the tool failure is not detected in time.

In micromilling unlike conventional machining, there are no handbooks available for selecting the machining parameters. For example, if the recommended cutting speed for conventional milling of aluminium is applied to micromachining, the calculated revolutions per minute will be approximately 350 000 for a 100-μm diameter cutter, which is clearly difficult to achieve. Also, in micromilling, special attention should be paid to burr formation at the end of each cut. Burrs are undesirable and it is very difficult to remove them from part microfeatures. Thus, it is very important to optimize the cutting parameters and machining strategies to avoid their formation.

Unfortunately, the existing simulation models for estimating cutting forces in a typical conventional end-milling operation cannot be applied directly in micromilling. It is necessary for these models to be adapted to the specific cutting conditions during micromachining or for new models to be developed. For example, a new analytical model was proposed to simulate micro-end-milling operations [**9**]. In this new model, the cutting forces are considered as a function of eight variables and one coefficient, and the cutter run-out is not taken into account. In particular, the following machining parameters are deemed important:

(a) three variables related to cutting conditions: spindle speed, feed rate, and width of cut;
(b) two parameters related to the applied machining strategies: the tool cutting entry and exit angle, which define the depth of cut, and the type of milling, up- or down-milling;
(c) and finally, three tool geometry variables: tool diameter, helix angle, and the numbers of tool flutes.

It is not difficult to see the advantages in applying this new model for estimating the cutting forces during micromilling. For example, if the machining is carried out with aggressive f_t (a higher f_t to r ratio), typical in micro-end-milling, the estimated forces by the new model differ significantly from those predicted by the general model and are much closer to the real ones. In particular, the difference between the cutting forces predicted by these two models will be more than 15 per cent if f_t to r ratio is higher than 0.1. The influence of the parameters identified as important for calculating the cutting forces have been studied in this research to develop efficient strategies for micromachining of thin features.

3 MICROMILLING OF THIN FEATURE

To machine successfully thin features at 'micro' scale, the following two issues are of significant importance.

1. The machining strategy should be selected by taking into account the specific geometry of the component. This includes the selection of cutting depth that keeps milling forces within predefined limits along the machining path.
2. The spindle speed and the feed rates should be chosen depending on the workpiece, the cutting tool materials, tool geometry, and chosen strategy [**10**].

In the general, when machining ribs and webs, the diameter of the cutter and the axial depth of the cut limit the cutting width. In addition, during the machining of thin features, the occurrence of high-frequency vibrations should be avoided. Thus, to comply with these constraints, several axial machining steps are necessary to machine ribs and webs to their desired depth and thickness.

To develop machining strategies that are specially designed for micromilling of thin features, the following considerations should be taken into account.

1. It is very important to avoid sharp corners at rib–web junctions. At such corners, fillets should be introduced to reduce the stress concentration and thus prevent part failures.
2. Sharp changes in the direction of the cutting forces should be avoided when machining ribs and webs. Especially, this is the case when ball-nose cutters are employed [**11**, **12**].
3. The axial component of the cutting forces should be kept within predefined limits, otherwise it could excite the workpiece and cause vibrations.
4. Special measures should be taken to avoid cutting tool breakages because small cutters are extremely vulnerable to varying process conditions.

The corner radius of the tools produces a component of the cutting force in the axial direction, which is enough to excite the workpiece and cause chatter [**13**, **14**]. Whereas the corner radii are necessary to produce fillets between the ribs and the webs (Fig. 1), there is no reason to use only ball-nose cutting tools during their machining. If thin features are machined completely using such cutters, this leads to a significant reduction of the material removal rates. This is because, the allowable step over distance between the passes should be reduced to less than half of the ball-nose radius to avoid the cusp. [**10**, **12**, **15**]

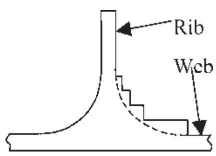

Fig. 1 Fillets between thin ribs and webs

To achieve vibration-free machining of thin features, it is a good practice to carry out such milling operations in two steps [16]. Initially, the features should be machined with the biggest possible diameter cutter with a zero corner radius, and just leaving sufficient material to form the fillets in the follow-up operation. Then, this machining allowance should be removed using a ball-nose cutter to produce a smooth fillet. To avoid the cusp, it is preferable that the allowable step over the distance between passes is less than half the length of the tool radius. The spindle speed for this operation should be set sufficiently low to benefit from the machine tool damping capabilities and thus to prevent chatter. However, it is not a trivial task to calculate this speed because it depends on the used workpiece material. The implementation of these general guidelines for milling ribs and webs will limit the occurrence of vibrations during the cutting and lead to the manufacture of features with a good surface finish.

In addition, other process parameters affect directly or indirectly the accuracy and surface quality of the machined thin features. These include side steps, step over movements, the depth of cut, feedrates per tooth, cutting speeds, cutting tool wear, and the use of cutting fluid/air/oil mist. The effects of these factors on micromilling process are discussed in reference [17] and in this research. They were taken into account in developing micromachining strategies for thin features and the software for calculating the machine parameters reported in reference [17] was used.

4 IMPLEMENTATION

Unfortunately, the general principles outlined in the previous paragraph are difficult to implement using the existing CAD/CAM packages. They could be implemented either by programming the milling operations manually or by developing a special CAM module for automatic generation of NC programmes. In this research both options are explored.

First, the tool paths that implement these general principles for micromachining of thin features were realized directly on a micromachining centre, KERN HSPC with Heidenhain TNC 426 controller, using its build-in milling cycles. In particular, the following two internal cycles were used to create NC programmes for machining ribs and webs.

1. Slot milling with reciprocating plunge-cut.
2. Pocket milling of a contour geometry (cycle 20). Its three 'sub'-cycles: rough-out (cycle 22), floor finishing (cycle 23), and side finishing (cycle 24) were applied.

Table 1 Process parameters

Tool: DIXI 7242R Flat end Tool diameter: 0.200 mm				Workpiece: Brass
Cutting parameters				
Cutting speed (m/min)	Spindle speed (RPM)	Feed/tooth (mm)	Step depth (mm)	Step over (mm)
18	39 000	0.007	0.005	0.070

The NC programmes were generated using internal Q parameters. Thus, it is possible the final contour of the machined feature to be composed of several overlapping contours.

In addition, the proposed strategies for machining thin features were implemented in a CAD/CAM environment. In this research, the Pro/Engineer environment was employed to develop a CAM module for their automatic generation. This included the design of a new internal machining strategy in the form of an Expert Machinist template in XML format [18].

An Expert Machinist template for each machining strategy studied in this research was created in Pro/Engineer for the KERN HSPC micromachining centre. Either default values or those recommended by the cutting tool manufacturers were utilized for all main parameters (Table 1). These templates were then used to modify the built-in machining strategies within the Pro/Engineer CAM module (marked as blocks 1, 2, and 3 in Fig. 2) to adapt them to the specific cutting conditions during micromachining. A program for calculating spindle speeds and feed rates for this Expert Machinist template was created and the respective tool database adapted to the specific requirements of this new internal strategy (marked as blocks 4 and 5 in Fig. 2). The second-order polynomial model developed by Lee and Dornfeld [15] and Lee [19] was applied to

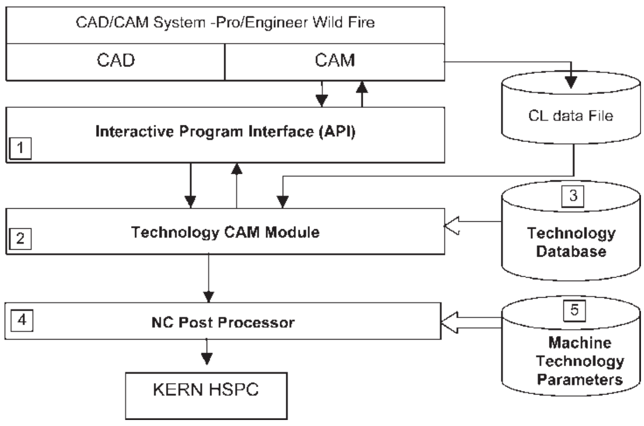

Fig. 2 The architecture of the CAD/CAM system

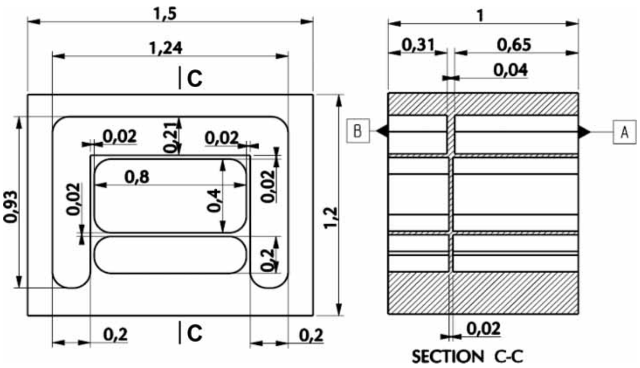

Fig. 3 Test part

calculate the chip load, depending on the final surface roughness

$$R_a = 43.6 + 439f_t + 46.3f_t^2 + 1256v_c - 990f_tv_c \qquad (1)$$

This equation depicts the relationship between chip load and surface roughness, especially when cutting at high speeds that are typical in micromilling.

To validate the tooling paths generated in both ways, a series of experiments was conducted.

5 EXPERIMENTAL VALIDATION

The test part proposed by Smith and Dvorak [**20**] was adopted in this study to validate the proposed strategies for micromachining. Using FEA methods, the dimensions of this part were calculated taking into account dynamic flexibilities, natural frequencies, and mode shapes of real webs. To adapt the part for use at microscale, it was re-designed by maintaining the ratios between its dimensions. The test part used in this research is shown in Fig. 3.

The machining of the test parts was carried out on a KERN HSPC 2216 micromachining centre. Its polymer concrete mono-block frame absorbs high-frequency vibrations much better than cast iron frames, which is very important for this experimental study. To generate 3D profiles of the machined thin features the relevant, areas of the test parts were scanned using a surface mapping system, MicroXAM. This is a surface profiler system using phase shift interferometry and vertical shift interferometry measuring principles with repeatability 1 nm (standard mode) or 0.1 nm (precision mode). Its calibrated accuracy is better than 0.1 per cent and lateral surface sampling from 0.11 to 8.8 μm. Workpiece vibrations during the machining were assessed visually employing a laser system, KEYENCE. This was carried out by focusing the reflected laser beam (50 μm spot size) from the workpiece on a target, a receiver, fixed on the machine. In addition, to study the quality of the produced ribs and webs under very high magnification, a Quick Vision measuring system was employed.

Brass workpieces were used in the experimental validation of the proposed machining strategies. The workpieces were machined to the state showed in Fig. 4 to prepare them for milling the thin features, with the ribs and webs positioned in the centre of the test part. This included the following machining operations:

(a) side A of the part is machined entirely;
(b) then, the U-type channel and the 800 × 200 μm^2 pocket on side B are machined to their full depth of 310 μm by applying reciprocating plunge-cut cycles.

The validation of the proposed strategies for machining thin features starts with the machining of the 800 × 400 μm^2 pocket located in the centre of the part. During this milling operation, the thin ribs around the pocket and the biggest webs of the part are formed. Three different strategies were used to machine this pocket.

1. In the first test, the milling was carried out using the 'standard' cycles that are commonly applied for machining such pockets at macroscale. In particular, Heidenhain Cycles 210 and 211 [**21**]

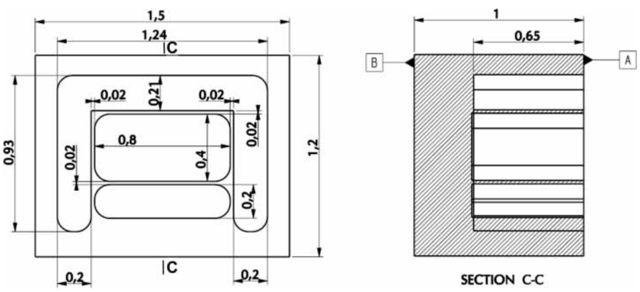

Fig. 4 Initial machining of Side B of the test part

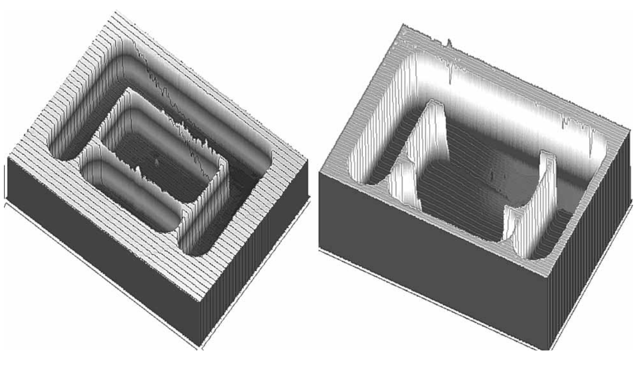

Fig. 5 Side B of two test parts scanned with the surface mapping system

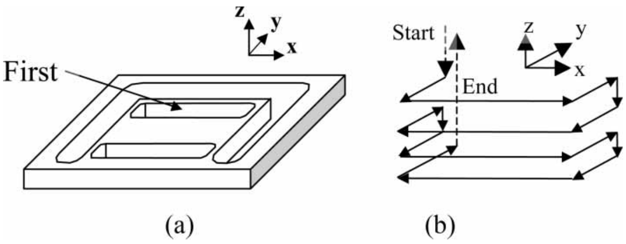

Fig. 6 Micromachining strategies

for slot and pocket milling with ramping were applied. The machining was carried out with a 200 μm diameter end-mill at a cutting speed of 39 000 rpm and feed rates of 70 mm/min. The resulting part is shown in Fig. 5. In this figure, it could be clearly seen that the ribs are bent and their thicknesses vary along the rib edge, and even some pocket walls are broken. The results of this test are used as a reference point to assess the improvements that the proposed new strategies bring to the machining of thin features.

2. In the second test, a two-step strategy was employed to machine the pocket with the same 200 μm diameter end-mill. Again, the spindle speed was 39 000 and the feed rate 70 mm/min. Initially, a slot, 800 × 200 μm, was milled to the final depth (Fig. 6(a)) applying a reciprocating plunge-cut cycle.

The tool path shown in Fig. 4(b) was then used to remove the remaining material layer by layer. The milling was carried out in a number of subsequent passes with an axial feed in the previously machined slot and thus without any cutting. In this way, it is possible to eliminate almost any axial forces during the milling and the cusp on the vertical walls. In spite of that vibrations occurred when machining the pocket due to continuing the reduction of part stiffness. As a result of these vibrations, the ribs do not have a consistent thickness as is shown in Fig. 7. Nevertheless, it should be noted that the part deformations are much smaller than those resulting from the use of standard pocketing cycles. It is obvious that this machining strategy is much more appropriate for milling thin features.

3. In the third test, a 150 μm diameter end-mill was used to machine the pocket in the centre of the test parts. The machining strategy was the same as in the previous test. The milling was carried out with spindle speed 40 000 r/min and feed rate 65 mm/min. An allowance was made for milling the fillets between the ribs and the webs in a follow-up operation using a 200 μm diameter end-mill with 25 μm corner radius. The spindle speed and the feed rate for this operation were 39 000 r/min and 70 mm/min, respectively. To avoid the web deflection, very small step depth

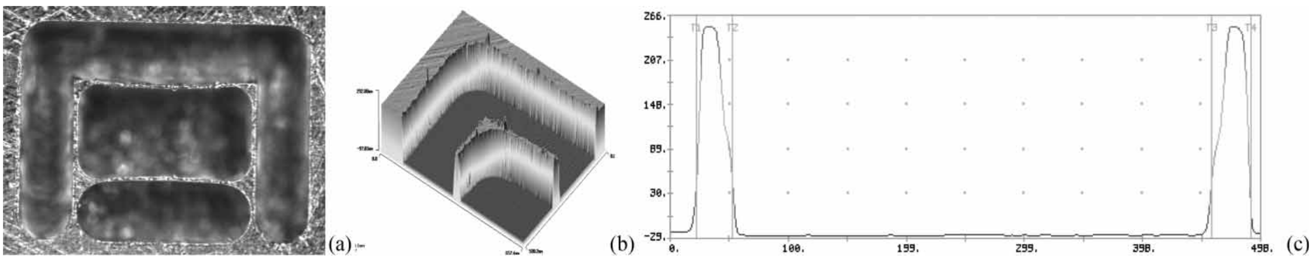

Fig. 7 Deformations caused by vibrations: (a) a quick vision picture; (b) a rib scanned with the surface mapping system; (c) the C–C cross-section of the ribs produced with the same system

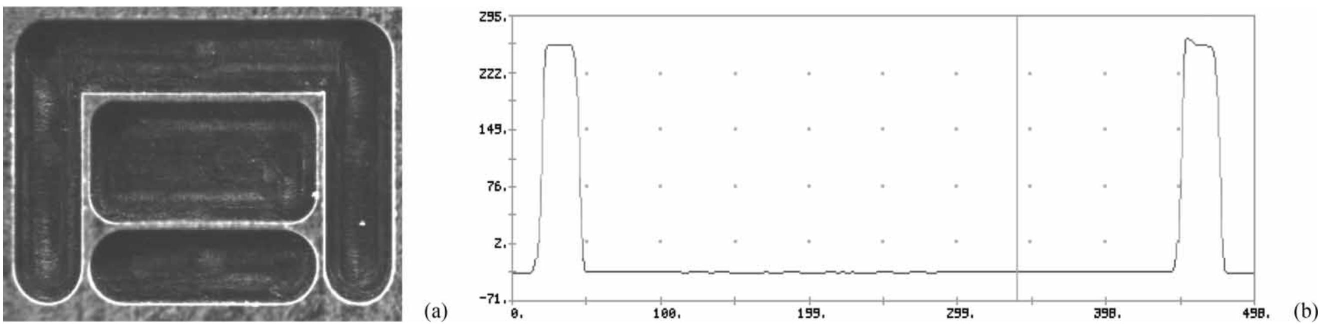

Fig. 8 The resultant part after almost vibration-free milling: (a) quick vision picture; (b) the C–C cross-section of the ribs produced with the surface mapping system

(7 μm) was used for all tests. The readings of the monitoring system indicated almost negligible vibrations during both milling operations. The quality of the machined test part reflects this. As can be seen in Fig. 8, the ribs are straight without any bending and also the C–C cross-section shows that the variation of the rib thickness is much smaller than in the previous test. Thus, it could be concluded that the machining strategy applied in the last test is the most appropriate one for milling thin features.

6 RESULTS AND CONCLUSIONS

This research reports an investigation of the main factors affecting the reliability of micromilling technology when employed for the machining of micro-components incorporating thin features. The general principles that should be followed in designing machining strategies for such features are described, and guidelines given for their correct implementation. Taking these general principles into account, new strategies are proposed to reduce the negative effects of identified factors on part quality, and at the same time to overcome some of the problems associated with the use of conventional machining strategies for micromilling of ribs and webs. In particular, the strategies for milling thin features should be designed taking into account the following main principles.

1. The tool path should be selected in such a way that the ribs and webs being machined are supported by specially designed fixtures or unmachined areas of the workpiece. Moreover, the cutting should proceed from the least supported area toward the best supported thin features in a component.
2. For thin webs, it is important to minimize the force component normal to the web. This means that most of the machining has to be performed using tools with no corner radius.
3. In case fillets are required between ribs and webs, they should be initially machined in a number of subsequent passes by removing the material layer by layer. Then, the resulting small steps will be removed in a follow-up milling operation using a cutter with the required corner radius. The machining of these steps should be carried out with spindle speeds that are sufficiently low to prevent any vibration occurring.

To implement and validate the proposed milling strategies, initially, NC programs for milling thin ribs and webs were created manually and then a special CAM module was developed for their automatic generation.

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