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6th CIRP Conference on Surface Integrity

Experimental investigation on surface integrity in a face milling operation

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This paper discusses the influence of surface milling on the surface integrity of a 15-5PH martensitic stainless steel. Among the surface integrity features, surface roughness and residual stress profiles are particularly studied. This experimental work aims at characterizing the sensitivity of three technological parameters, namely the number of teeth, the axial runout of the milling cutters and the tilt angle. On these features, it is shown that the surface roughness is determined by the axial runout of the milling cutter when milling with multiple cutters without tilt angle. In contrast, the residual stress state is not significantly affected by any of these parameters.

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Keywords: Face-milling; Residual stresses; Spindle tilt; Teeth number**1. Introduction**

The fatigue resistance of critical components is correlated to the surface integrity of highly loaded areas [1]. Surface integrity is characterized by several features: residual stress profiles, microstructure and surface roughness. The finishing process plays a dominant role in surface integrity. As far as flat surfaces are concerned, the face milling process (Fig. 1) is the favorite solution as this process is productive and easy to handle on any machining centers.

The face milling operation is governed by a collection of parameters: the selection of the mill (number of teeth Z , cutter diameter, ...) and the corresponding errors (manufacturing + assembly errors) leading to cutter's runout (axial ϵ_a and radial ϵ_r runout), the cutting parameters (V_c , a_p , f_z , ...), the lubrication conditions (composition, flow rate, ...). All these parameters are expected to influence the surface integrity.

As far as residual stresses are concerned, the scientific literature [2, 3] reports that a surface milling operation of a steel part induces tensile stresses on the external surface, followed by a small compressive state in the subsurface. The affected depth is rather limited in the range 20 to 40 μm [2, 3]. That is much

smaller compared to turning [4]. Several papers have already summarized that residual stresses are induced by the thermo-mechanical loadings [4] applied by the teeth on the surface in the cutting zone in front of the mill (Fig. 1b). Several authors, such as [1], have shown that heat generation in the cutting zone favors tensile stresses, while plastic deformation are more likely to induce compressive stresses.

Several papers have investigated the sensitivity of residual stresses to cutting conditions. For example, [2, 3] showed the high sensitivity to the feed per tooth f_z and to the depth of cut a_p , while cutting speeds does not seem to be significant [3].

As far as the design of the mill is concerned (number of teeth, angles, cutter's geometry, ...), the scientific literature does not report any work. However, the number of teeth should be a sensitive parameter as it determines the frequency of the thermomechanical loadings applied on the surface. Hence, there is a clear interest to investigate the influence of the number of teeth.

The same statement can be made on the lack of scientific works dealing with the influence of the contact between the milling cutters on the back side (Fig. 1b). Depending on the tilt angle (Fig. 2a), cutters may be in contact in this back area as

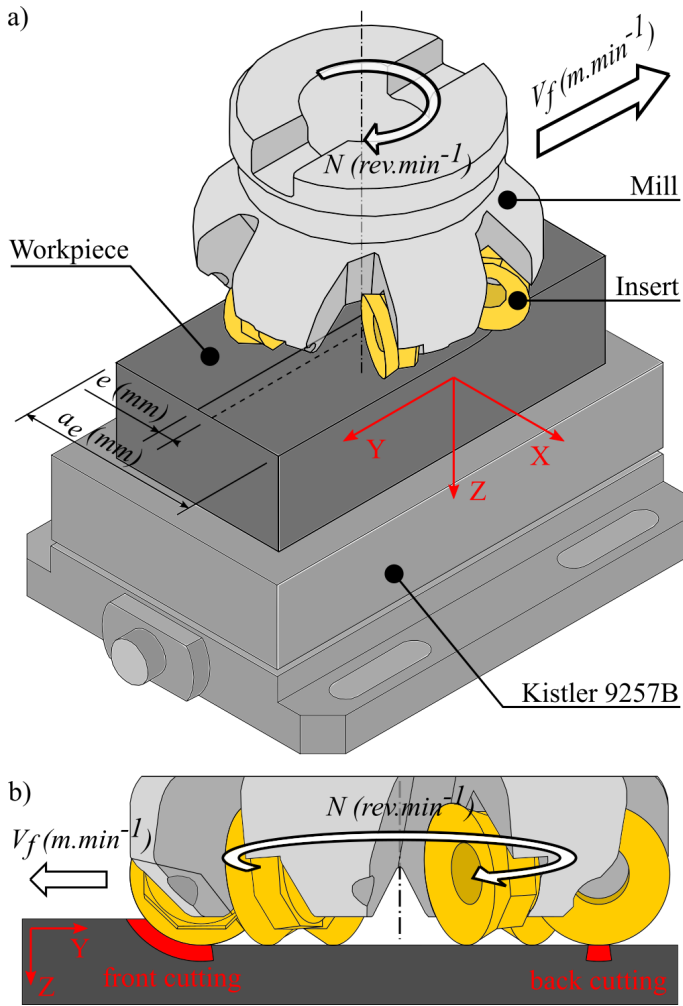


Fig. 1. Surface milling experimental setup.

shown by [5]. This may modify the residual stress state by removing a small amount of material or by ploughing the surface, that induces a second thermomechanical loading on the surface. Hence, there is a clear interest to investigate the influence of the tilt angle.

Finally, it is well known that the position of milling inserts varies around a theoretical value selected by the mill manufacturer. This variation is quantified by means of two parameters: the axial runout ϵ_a and the radial runout ϵ_r as illustrated in Fig. 3a. The runout leads to a variation of the cutting phenomena among the inserts, and as a consequence to a variation of the thermomechanical loadings on the surface. It is also responsible for the contact of the inserts in the back area. Hence, the influence of insert's runout on the residual stress state in surface milling has not been investigated in the scientific literature.

As far as surface roughness is concerned, the scientific literature has shown that surface roughness is mainly influenced by geometrical parameters (insert radius and feed per tooth f_z) when the teeth are only in contact in the cutting zone (front area of the mill) (Fig. 1). This situation can only be ensured by the presence of small tilt angle (tenth of degree). In this context,

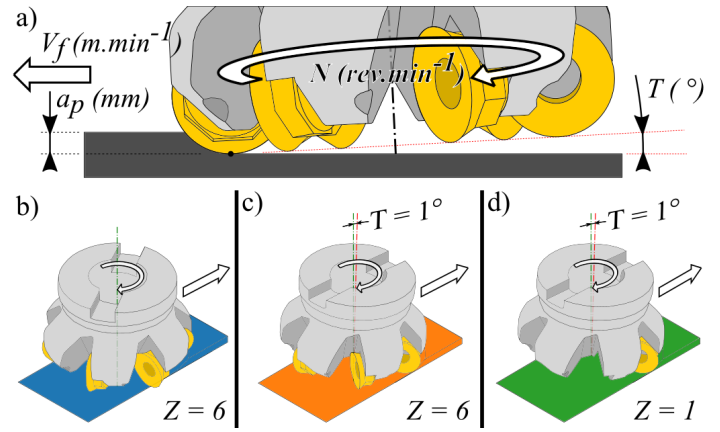


Fig. 2. (a) Illustration of the tilt angle T - (b) Configuration 1: $Z = 6, T = 0^\circ$; (c) Configuration 2: $Z = 6, T = 1^\circ$ and (d) Configuration 3: $Z = 1, T = 1^\circ$.

the scientific literature has shown the key influence of the axial cutter runout ϵ_a [6].

In the absence of tilt angle, the contact of the milling cutters in the back area becomes possible, which fully changes the surface roughness. However, the effect of the axial runout remains predominant.

As a summary, this work aims to investigate the influence of the number of teeth, of the axial cutter runout and of the tilt angle on surface integrity using an experimental approach. Surface roughness and residual stress profiles were characterized. Milling operations have also been monitored using a dynamometer to correlate surface integrity features with the mechanical action of the mill.

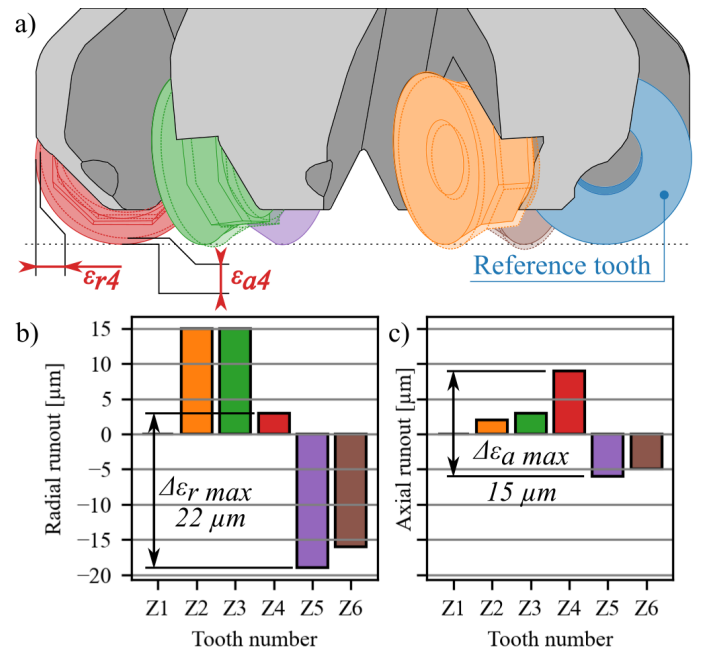


Fig. 3. (a) Illustration of axial and radial insert runout; (b) Axial runout ϵ_a and (c) Radial runout ϵ_r of the 6 inserts.

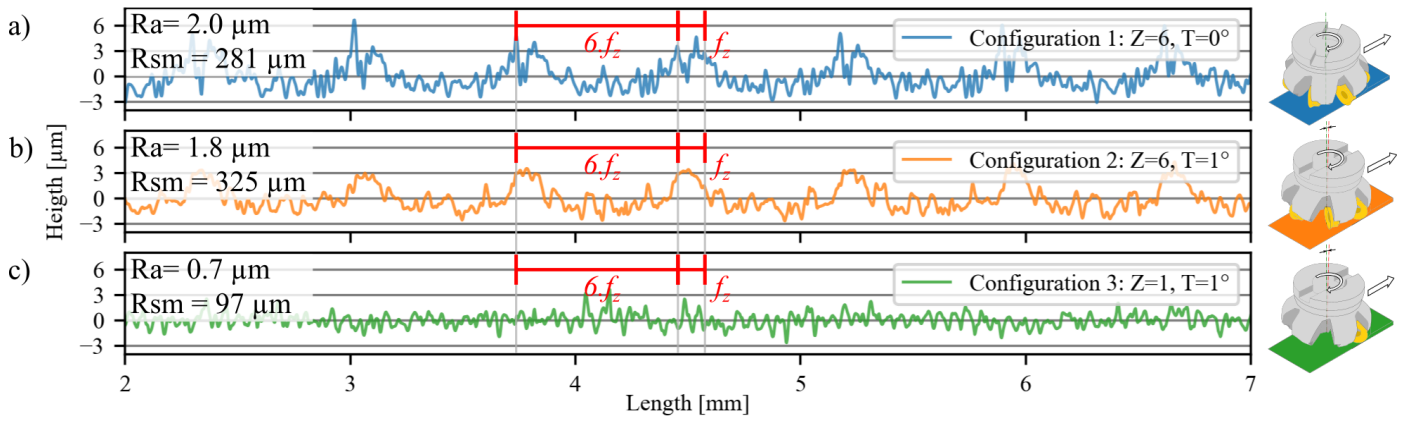


Fig. 4. Roughness profiles extracted from the green line on Fig. 5 for each configuration with the mean values for Ra and Rsm criterion.

2. Experimental setup

Face-milling experiments were conducted on flat surfaces of 15-5PH martensitic stainless steel with a dimension of $110 \times 40\text{mm}$ on a machining center (Fig. 1). The milling cutter used was an ISCAR SOF45 8 16-D050-06-22R (diam. 50mm – 6 inserts) equipped with ISCAR RXMT 1607N IC830 inserts. Tests have been performed in dry conditions. The width of the surface a_e was set to 40mm which corresponds to a radial engagement of 75% of the milling cutter diameter. The axis of mill was shifted of $e = 3\text{mm}$ from the center of the workpiece (Fig. 1).

The cutting parameters used are $V_c = 120\text{m}\cdot\text{min}^{-1}$, $f_z = 0.12\text{mm}$ per tooth, $a_p = 0.5\text{mm}$. Depending on the configuration, a tilt angle T of 0° or 1° was used and the number of teeth Z was set to 6 or to 1. When milling with only one tooth, the feed per tooth f_z and the cutting speed V_c were kept constant.

Three configurations were investigated as shown in Fig. 2b.

The 1st configuration corresponds to the reference with 6 teeth and the absence of tilt angle (Fig. 2b).

The 2nd configuration investigates the influence of the tilt angle $T = 1^\circ$ (Fig. 2c) with $Z = 6$ teeth. The same mill has been used for the configurations 1 and 2, so that the axial runout of inserts were similar.

NB: The axial (ϵ_a) and radial (ϵ_r) runout of each insert were measured using a profile projector. Both radial and axial runout values are reported in Fig. 3b and 3c.

The 3rd configuration investigates the influence of the number of teeth $Z = 1$ combined with a tilt angle $T = 1^\circ$ (Fig. 2d). The concept of axial runout has no meaning in this case.

Surface milling operations were monitored thanks to a three-components dynamometric table Kistler 9257B as shown in Fig. 1.

Surface roughness were measured using a confocal microscope with a $\times 10$ magnification. 2D profiles (12.5mm length) were extracted and surface roughness parameters Ra (average surface roughness) and Rsm (mean spacing of profile irregularities) were quantified after a filtering step (Gaussian filter + cut-off $L_c = 2.5\text{mm}$) (Fig. 4).

Finally, residual stresses were measured along the longitudinal (Y) and transverse (X) directions using a X-RayBot ma-

chine with a Chromium (Cr) tube and a Vanadium (V) filter. For each configuration, 3 residual stress profiles have been measured. The pre-stress eventually induced in the sample was neglected in regards to the depth of cut.

3. Results and Discussions

3.1. Surface topography

Figure 5a to 5c presents the surface topography obtained for the 3 testing configurations and the corresponding values of surface roughness parameters Ra and Rsm.

Fig. 4 plots an example 2D surface roughness profiles.

By comparing Fig. 5a and 5b, it appears that both surfaces have similar surface roughness Ra and similar 2D roughness profiles (Fig. 4a and 4b). Nevertheless, the two surface textures are inverted. As illustrated in Fig. 6a, in the reference case study (Fig. 5a - $Z = 6 - T = 0^\circ$), inserts machined the surface for a second time in the back area. We call this phenomenon back cutting [7]. On the contrary, thanks to the tilt angle (Fig. 5b and Fig. 4b), the surface topography, for the 2nd configuration, is induced by the frontal area only as illustrated in Fig. 6b.

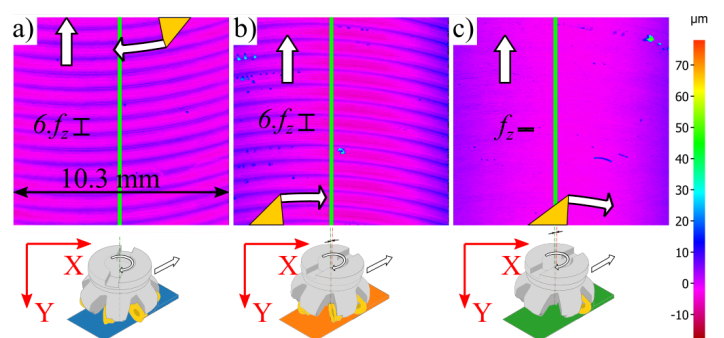


Fig. 5. Surface topographies for (a) configuration 1 ; (b) configuration 2 and (c) configuration 3. A tooth (on scale) is represented on each topography and the values of both the feed per tooth f_z and $6 \cdot f_z$ are shown. The green lines marked the area where the roughness profiles were extracted.

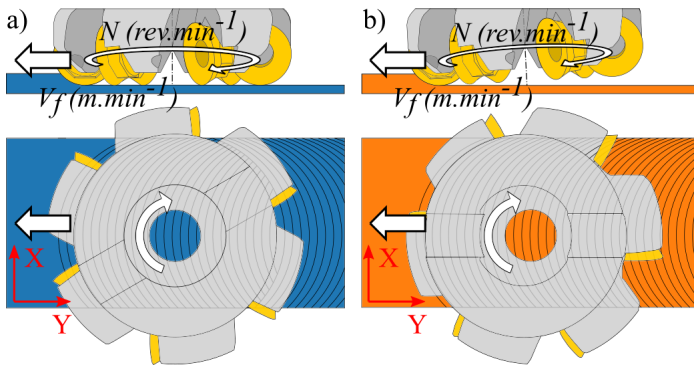


Fig. 6. Surface topography produced (a) firstly by the front teeth + by the back teeth when there is no tilt angle and (b) the front teeth only where the tilt angle is high enough to prevent the back teeth from touching the machined surface.

By comparing Fig. 4b and 4c, that corresponds to the tests with $Z = 6$ or $Z = 1$ with tilt angle $T = 1^\circ$, it appears that the two profiles are different. Fig. 4b reveals a period corresponding to 6 feed/tooth ($6 \cdot f_z = 0.72mm$), which means that the signature of the mill is imposed by a single tooth due to its dominant axial runout. On the contrary, the 3rd configuration (Fig. 4c) with a single tooth leads to a homogeneous surface roughness. A similar conclusion can be made by comparing the two mean spacing of profile irregularities R_{sm} . The presence of a runout increases R_{sm} from $97\mu m$ to $325\mu m$.

3.2. Forces

During surface milling operations, the mechanical action of the mill on the part were measured thanks to a dynamometer (Fig. 1a). An example of the evolution of the axial force F_z (here called penetration forces) and the cutting forces (calculated as the resultant of the forces along the X and Y direction of the dynamometer) measured during the reference case study (Fig. 1) is plotted in Fig. 7. As expected, forces vary from the entrance of the milling cutter to the exit of the mill. The steady state zone corresponds to the stabilized zone where the whole mill is engaged in the front and in the back area.

A comparison of the three figures (Fig. 7a to 7c) reveals that the contact between the mill and the machined surface remains for a longer time for the reference case study (Fig. 7a) due to the contact between the back teeth and the machined surface. On the contrary, the presence of a tilt angle leads to a reduced contact duration (Fig. 7b and 7c), i.e no signals is observable in the back cutting zone.

By comparing the magnitude of the forces between the configuration 1 and 2 (without or with a tilt angle), it reveals that the tilt angle led to increased measured forces as the back cutting phenomenon disappears in the last zone. For instance, the maximal penetration force F_z is increased from $\approx 850N$ to $\approx 1100N$ in the steady state zone as shown in Fig. 8a and 8b. This is due to the absence of contact in the back area. As a matter of fact, the back cutting generates cutting forces in the opposite direction of the cutting by the front teeth, thus reducing the global forces measured by the dynamometer. However, in the case of

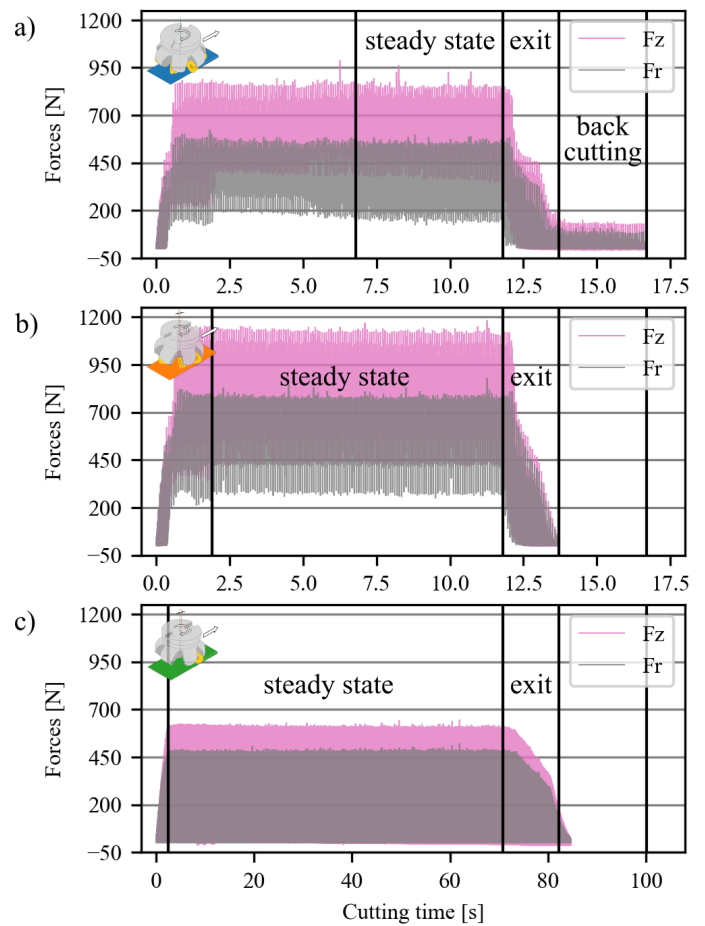


Fig. 7. Cutting and penetration forces (from the entrance to the exit) for (a) configuration 1; (b) configuration 2 and (c) configuration 3.

the penetration forces F_z , the front and back teeth both participate to increase its value.

By comparing the shape of the signals between the configuration 2 and 3 (with $Z = 6$ and $Z = 1$), the signals are much more disturbed with several teeth than with a single tooth. Fig. 8 plots a zoom in the steady state zone for each configuration. As expected, the configuration 3 ($Z = 1$) in Fig. 8c leads to an interrupted cut, whereas the configurations 1 and 2 ($Z = 6$) lead to a permanent contact and as a consequence to a higher average force. On the contrary, each elementary signals remain

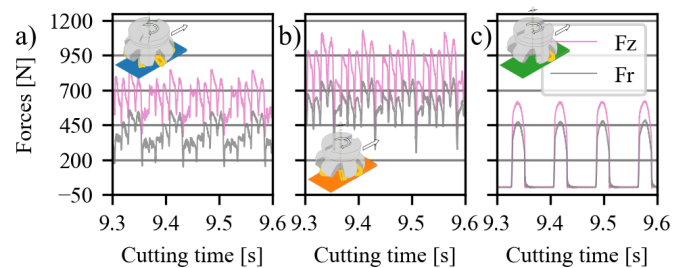


Fig. 8. Evolution of the cutting and penetration forces during the steady state for (a) configuration 1; (b) configuration 2 and (c) configuration 3.

stable for the configuration 3 ($Z = 1$). The signals vary from one tooth to another one. A period corresponding to 6 feed per revolution is observable. This is because of the axial and radial runout of the 6 inserts (Fig. 2).

3.3. Residual stresses

The position of the measuring area on the surface is illustrated in Fig. 9a, at the center of the workpiece where the forces were in their steady state.

As the spot size is around 1mm diameter, and the feed per tooth is around 0.12mm, the X-Ray signals' average the residual stress present in 8 to 9 grooves as illustrated in Fig. 9b.

For each testing configuration, 3 residual stress profiles were measured. A natural deviation exists. So, it has been decided to plot the 3 residual stress curves as a cloud surrounding the maximum and the minimum. The cloud takes into account the measuring uncertainty of the X-ray machine and the variation

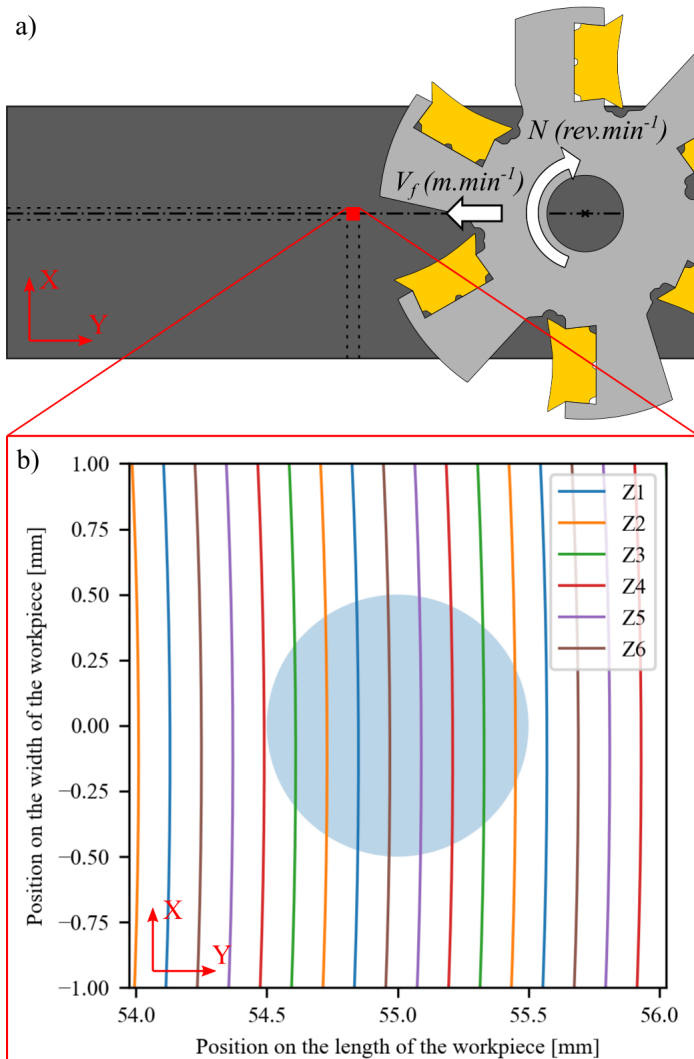


Fig. 9. (a) Area for residual stress measurements (b) teeth trajectories and X-ray spot.

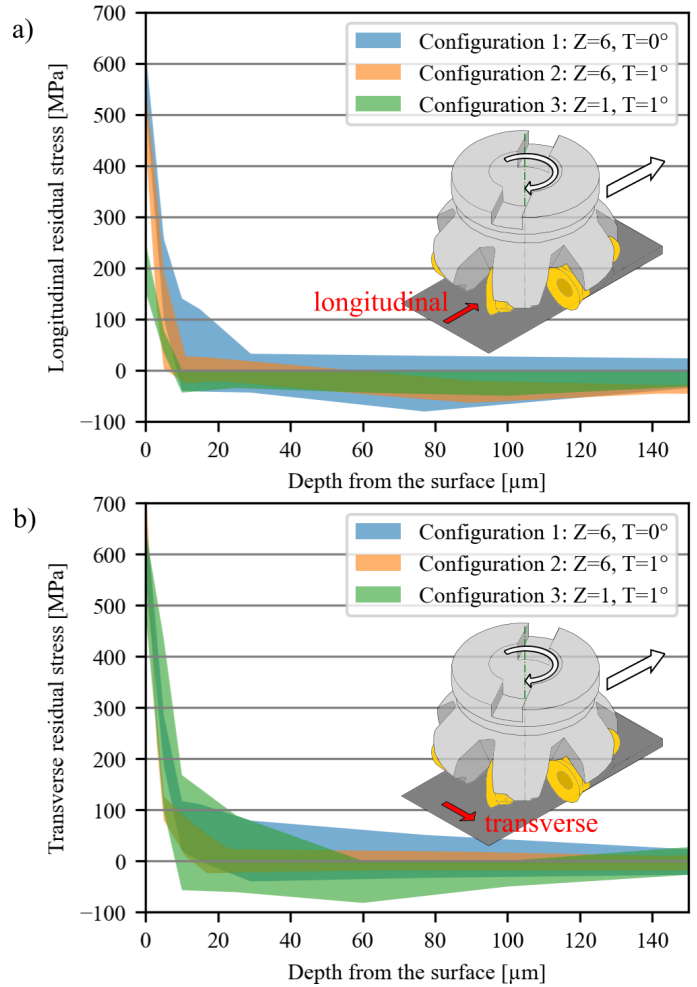


Fig. 10. Residual stress profiles for the 3 configurations along (a) the longitudinal (Y) and (b) the transverse (X) directions.

of the measured forces. Fig. 10a plots the 3 clouds of residual stresses obtained for the longitudinal (feed) direction Y and Fig 10b plots the results for the transverse direction X.

An overall observation of the residual stress curves reveals that the external layers are always in tension for the three configurations. It seems that surface milling is mainly governed by thermal issues in the present case study.

A second overview on the three residual stresses clouds shows that the affected depth is in the range between 10 to 30μm. This thickness is rather limited compared to the 120 to 150μm of affected depth obtained in turning for the same 15-5PH alloy as shown by [4], but it is consistent with previous research works [2, 3]. This shows that the intensity of the thermomechanical loadings applied by milling is much more limited compared to the one induced by turning. However, the thickness of the affected layer does not seem to be significantly sensitive to the 3 testing conditions.

The three clouds are very similar and the differences are not higher than the deviation of a single testing condition. It is only possible to observe a significant difference among the three clouds of residual stresses in the external layer. It appears, that

milling with 6 teeth (config. 1 & 2) tends to increase the tensile stresses in the feed direction within the external layer, compared to the milling operation with a single tooth (config. 3). The main difference comes from the frequency of the thermo-mechanical loadings applied on the surface. For configuration 1 and 2, the frequency is 6 times higher. So, there is a limited time for the workmaterial to cool down by heat conduction in the bulk of the part. Therefore, the temperature remains higher on the surface. This promotes the generation of tensile stresses.

It was shown that the roughness profile for configurations 1 and 2 (without or with tilt) are not the same (Fig. 4a and 4b). Then, the first 10 to 20 μm must have been overwritten by the action of the back cutting, and along the roughness, the residual stress must have changed too. However, it was stated previously that the configurations 1 and 2 lead to very similar residual stress profiles. Nevertheless, in the configuration 2, cutters are only in contact in the frontal area, whereas in the configuration 1, cutters are in contact in the frontal area and in the back area. Furthermore, the evolution of the forces in the back cutting zone (Fig. 11) show that the intensity of the forces generated by the back teeth are a lot lower than the one generated from the front teeth ($\approx 130\text{N}$ against $\approx 1150\text{N}$) and that some of the back teeth are not cutting, leading to discontinuous forces. This is due to the low depth of cut of the back teeth the axial runout that prevent some of them from cutting. Such dissimilar forces should lead to different thermomechanical loadings and thus to different residual stress profiles but it's not the case. The common point between these two configurations is the rubbing of the flank face of cutters on the machined surface. This let us assume that rubbing on the flank face should be the dominant mechanism generating residual stresses. In this area, friction, and the corresponding heat generation, play the dominant role to generate tensile stresses similar on both sides.

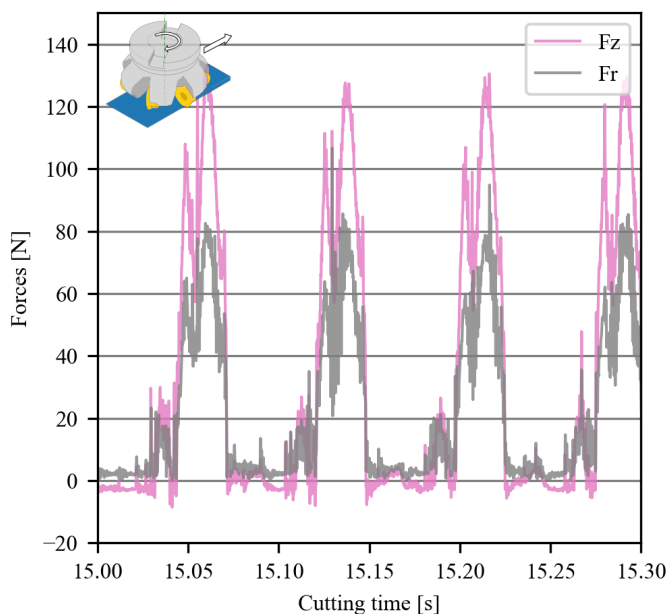


Fig. 11. Cutting and penetration forces within the back cutting zone of configuration 1 where only the back teeth are still cutting the surface of the workpiece.

4. Conclusion

This paper has investigated the sensitivity of some face milling technological parameters (number of teeth, axial runout of inserts, tilt angle) on surface integrity. Surface roughness and residual stresses were characterized after 3 milling configurations combining the previous parameters. Force measurements have enabled to analyze cutting mechanisms.

It has been shown that surface roughness is mainly determined by the axial runout of inserts irrespective of the tilt angle. By the way, the best surface roughness can be obtained when milling with a single tooth.

As far as residual stress generation is concerned, it is highlighted that the heat generation in the rubbing zone between insert's flank face and the workmaterial seems to be the dominant mechanism. The three investigated technological parameters induce similar profiles with a tensile stress in the external layer and a narrow-affected depth. The use of several inserts induces additional tensile stresses.

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