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DIMENSIONAL AND GEOMETRIC DEVIATIONS INDUCED BY FACE MILLING OF AISI D2 TOOL STEEL

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Abstract. *Surface quality is a fundamental aspect of the manufacture of dies and molds, which must be produced in accordance with tight tolerances in order to ensure high quality components. The costs associated with the manufacture of dies and molds are very high and, therefore, milling of cavities plays a vital hole in the productive chain, since the machining and finishing steps represent approximately 80% of the total cost of the die/mold. The present work is concerned with the analysis of the contribution of tool deflection on dimensional and geometric deviations induced by milling of AISI D2 tool steel. The developed measurement system is based on of laser triangulation. Tests were conducted under different cutting conditions aiming to assess the influence of the cutting parameters (cutting speed, feed rate, depth and width of cut) on tool deflection and workpiece quality (dimensional deviation, flatness and surface roughness). The results indicated that tool deflection can be accurately determined using the proposed technique and that depth of cut is the most influential parameter affecting tool deflection and surface quality.*

Keywords: *Milling, tool deflection, surface quality, dimensional deviation, AISI D2 tool steel.*

1. INTRODUCTION

The manufacture of dies and molds plays a key hole in many different industrial sectors owing to the fact that the majority of mass produced parts are manufactured through processes that employ dies and molds. In general, these components must be produced with acceptable accuracy in order to ensure tight dimensional and geometric tolerances. The surface quality of dies and molds directly affects the quality of the final component and, therefore, its design and manufacture represent a crucial aspect of the entire production chain (Altan, 2001).

The process by which a die or mold is manufactured may vary according with several factors such as size, complexity and cost. Small dies are generally machined and then polished while in the case of larger dies their manufacture can be divided into three steps: casting, machining and try-out.

According to Altan (2001), in the case of automotive components, dies may cost up to US$500.000 and require from 6 to 9 months for try-out and robust process development using production equipment. Despite the high cost of tooling and equipment, the investment in dies and molds, as well as in machine tools, may be considered small compared to the total production cost.

1.1 Surface quality

As previously discussed, surface quality is an essential aspect in the manufacture of dies and molds. The final condition of a machined surface results from a process which involves plastic deformations, fracture, elastic recovery, heat generation, vibrations, residual stresses and even chemical reactions (Machado, *et al.*, 2011).

Dimensional deviations correspond to the difference between actual and theoretical dimensions while geometric deviations correspond to the difference between actual and theoretical geometries features. In the present work, the deviation of the milled width along a straight segment and the flatness of a machined surface were evaluated. In machining of dies and molds, the surface texture is also important even when the component is subsequently polished. Better finishing reduces further grinding and polishing operations and, as rule of thumb, revolution ridges larger than the width of half finger (about 5mm) cannot be manually polished (Knobel, 2000).

Weck (2006) states that the principal factors which affect the geometric deviations of machined surfaces are tool wear and built-up edge; dynamic effects of the machine tool (e.g. deviation of linear or rotary movement); elastic deformation of the machine tool, workpiece and especially cutting tool and accessories. As far as the milling operation is concerned, the main causes of geometric errors are tool deflection and vibrations, therefore all factors which affect the cutting force assume special importance. Besides the contribution of mechanical effects involved in the process,

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dimensional and geometric deviations can be related to thermal effects and workpiece/tool fixture errors (Machado et al., 2011).

Surface roughness is characterized by fine irregularities (in the micrometer scale) as the result of cutting tool action. Tool geometry and feed rate are the principal factors affecting surface roughness. The surface quality of molds is even more important when superior finishing of final component is required, particularly in the manufacture of transparent surfaces through the injection process (Ribeiro, 2007). For this reason, there are many theoretical models available which allow predicting the roughness with relative accuracy, although there are other variables that can also affect it, especially the machining force. The machine force may increase the amplitude of the excited vibrations and consequently the roughness. Thus, all the factors that cause an increase in the machine forces may directly or indirectly affect surface quality.

1.2 Machining forces and tool deflection

Machining forces are responsible for tool deflection and the relation between them is approximately linear. In the particular case of milling, cutting forces vary along one revolution of the tool. Consequently, tool deflection has the same periodic behavior with phase angle, as experimentally shown by Deonisio (2004). As a result of force increase, tool deflection leads to machining errors: the average tool deflection causes lower material removal (dimensional deviations) while the dynamic tool deflection causes geometric deviations. The latter can also be related to mechanical vibration of the system, which has a considerably effect on surface roughness.

In an ideal milling operation, the cutting force can be described as a sinusoidal function of the angular position of the cutting tool (Ribeiro, 2007). However, it does not occur due to the dynamical complexity of the milling operation and many researchers are concerned with the development of models capable of predicting its behavior (Smith e Tustly, 1991; Altintas, 2000; Habibi, *et al.*, 2011; Ko, *et al.*, 2002; Omar, *et al.*, 2007). A cantilever beam model is commonly used to predict tool deflection and this method gives a rapid evaluation of the milled surface. Law et al. (1999) obtained satisfactory results using this model to predict tool deflection along a straight cutting path: both radial and feed forces and tool deflection increased linearly with width of cut. Using a cutting path compensation method, the authors were able to reduce machining error by approximately 57%. However, according to Liu et al. (2002) the machining error is not directly proportional to tool and workpiece deflection due to cutting forces. Dépincé and Hascoët (2006) proposed an approach based on a contact point method to predict the milled surface and obtained more accurate results than the traditional cantilever beam model.

In addition to that, tool deflection depends on tool path. An error compensation model developed by Law and Geddam (2003) distinguishes between straight line and corner sections. Experiments with different cutting modes showed that deflection errors vary particularly in corner sections (Law, *et al.*, 1999). A typical strategy to minimize tool deflection and decrease milling cutter deflection errors in corner sections is to reduce the radial depths of cut.

1.3 Tool deflection parameters

As previously mentioned, tool deflection is approximately proportional to the radial component of the cutting force. Since tool deflection varies along the revolution Φ of the tool, it is important to define parameters to quantify tool deflection (see Fig. 1). The maximum tool deflection (δ_{Max}) is the largest deflection value obtained along one revolution, while the average tool deflection ($\delta_{Average}$) corresponds to the mean value calculated for a complete revolution (see Eq. 1).

$$\delta_{Average} = \frac{1}{2\pi}\int_{0}^{2\pi} \delta(\phi).d\phi \qquad (1)$$

The average cutting deflection (δ_{Cut}) is defined as the mean value for the tool deflection calculated during the period of revolution in which actual cutting takes place, i.e., while the tooth removes material (see Eq. 2).

$$\delta_{Cut} = \frac{1}{2\pi}\int_{\phi_1}^{\phi_2} \delta(\phi).d\phi \qquad (2)$$

The equations above (Eq. 1 and Eq. 2) correspond to basic statistical functions defined for the particular boundary conditions.

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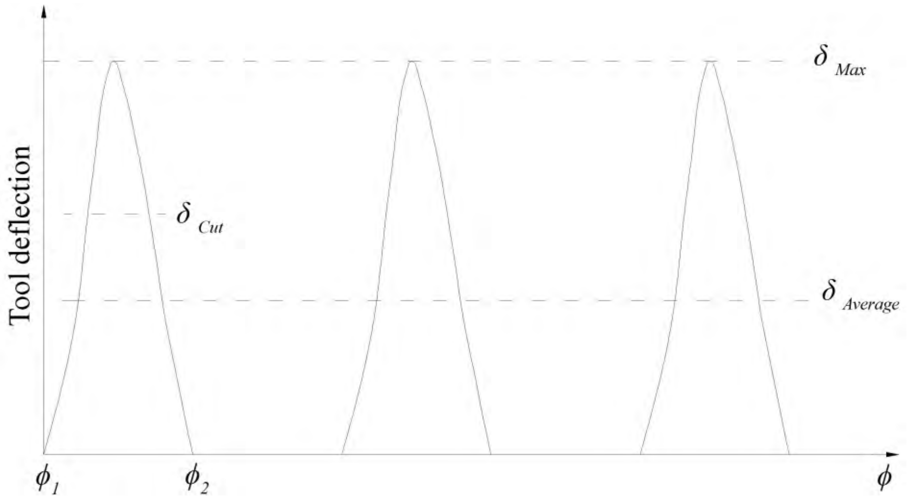

Figure 1. Tool deflection parameters.

The laser system developed in the present work measures only the average cutting deflection δ_{Cut}, since it acquires the signal during the period of revolution in which cutting takes place (see section 2.1).

1.4 Measurament methods

For the measurement of distance and displacement, non-contact methods are preferable in order to avoid the application of force (Nakazawa, 1994; Dornfeld and Lee, 2008). When force is applied to a surface, it induces contact tension and, consequently, local deformation. The flatness may be calculated by the Hertz equation and this error can be compensated. However, contact measurement methods during milling operation are unfeasible and, for this reason, non-contact methods seem to be the best approach.

There are basically two types of non-contact measurement systems: electromagnetic (inductive, capacitive, etc.) and optical systems (triangulation, laser interferometry, shadow and projection). Measurement systems based on laser interferometry present high resolution but are sensitive to external factors, especially vibrations. Nevertheless, the need for continuous acquisition makes this technique impracticable in the case of intermittent operations, such as milling. In this case, a perfectly cylindrical mirror around the cutter would be necessary.

The selection of a measurement system based on laser triangulation is mainly due to its simplicity. Additionally, its measurement range varies from 1 to 100 mm and the accuracy up to 0.25%. There are optical triangulation sensors commercially available, which are capable of measuring from 0.5 to 1000 mm with resolution up to 0.0015% (Micro-Epislon, 2012).

2. EXPERIMENTAL PROCEDURE

Milling tests were conducted on a numerically controlled machining center with 9 kW of power and maximum rotational speed of 7500 rpm. Six blocks of AISI D2 tool steel (average hardness of 210 HV) with initial dimensions of 170x100x15 mm were used as work material. A intentionally slender milling cutter from Sandvik Coromant coded R-390-016A16L-11L (two teeth, nominal diameter of 16 mm and overhang length of 80 mm) was used together with PVD coated carbide inserts (Sandvik Coromant code R390-11T312E-PM, tool grade GC1010).

For each test, the average cutting deflection (δ_{Cut}) was measured using the developed measurement system. This value was correlated to the dimensional deviation (milled width), surface flatness and machined surface roughness (R_a and R_z parameters). Table 1 presents the cutting speed (v_c), feed rate (f_z), width of cut (a_e) and depth of cut (a_e) used in each test.

Table 1. Cutting conditions.

Test	v_c [m/min]	f_z [mm/tooth]	a_e [mm]	a_p [mm]
1	60	0.05	4	1
2	120	0.05	4	1
3	60	0.10	4	1
4	60	0.05	8	1
5	60	0.05	4	2
6	60	0.10	8	2

2.1 Tool deflection measurement

An optical system based on the laser triangulation principle was developed to measure the average cutting deflection (δ_{Cut}). A He-Ne laser source with 5 mW of power emits a beam which is reflected by a small mirror attached to the cutting tool (above one of the teeth) on a screen (see Fig. 2). A CCD camera was used to record light projection on the screen.

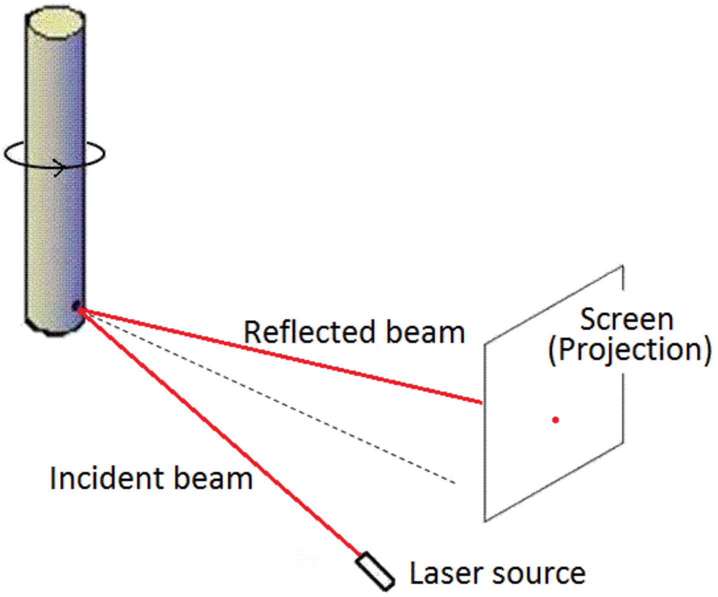

Figure 2. Principle of laser triangulation.

To measure the displacement of the laser beam projection on the screen, an algorithm was developed using the software Matlab, which compares the position of the projection with a reference value corresponding to its initial position (non-deflected tool). The relationship between tool deflection and the projection path is approximately linear.

In order to calibrate the system, a steel block fixed in the machine tool table was used to induce a previously known static tool deflection. Since the positioning system of the machine tool may not be accurate enough and there is local deformation of the tool and workpiece, a dial gauge indicator was used as a reference measurement system to establish the relationship between tool deflection and the position of the projection path on the screen (see Fig. 3).

The graph in Figure 4 shows the relationship between the values measured using the two systems, i.e., the developed optical triangulation system and the dial gauge indicator during the calibration procedure. The maximum error is approximately 5 µm.

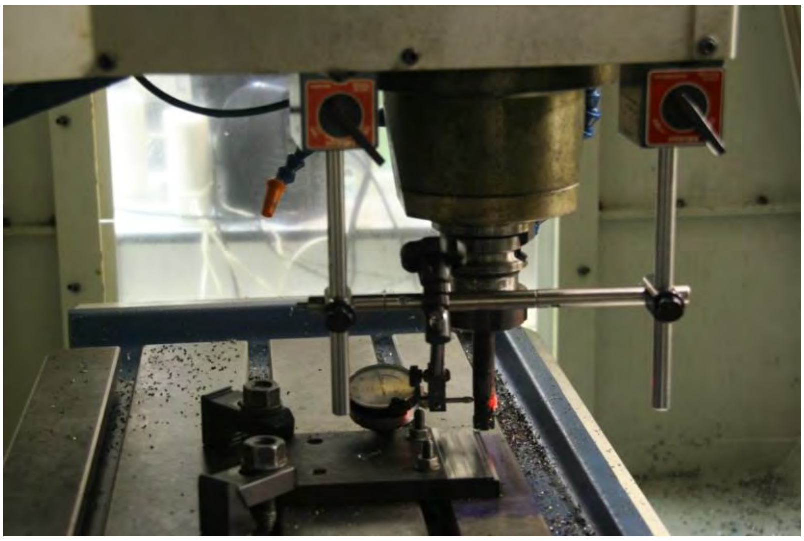

Figure 3. Calibration of the measurement system.

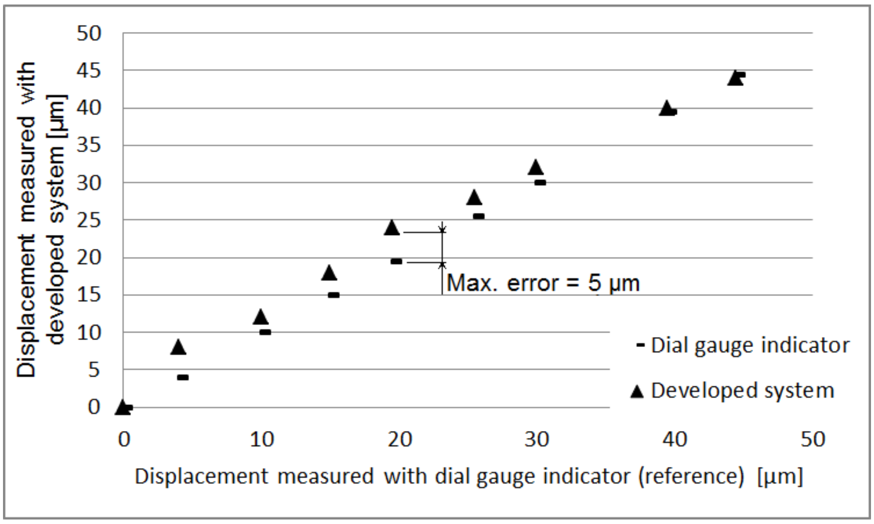

Figure 4. Tool deflection measured by the developed system and by the dial gauge indicator.

The developed system captures the signal only while the laser beam reaches the mirror, i.e., it measures tool deflection only while the insert below the mirror is cutting material. Therefore, this system does not measure the average deflection of the tool, but the average cutting deflection δ_{Cut}. The acquisition rate of the CCD camera is at the same frequency magnitude of the laser beam incidence on the screen (approximately 30Hz). The camera alternately records empty frames and frames that contain the laser projection (see Fig. 5). The difference between the frames provided by loaded and unloaded tools was used to determine the average cutting deflection. Although the acquisition rate may not be high compared to the cutter rotation, it allows the calculation of the statistical parameters defined in section 1.3.

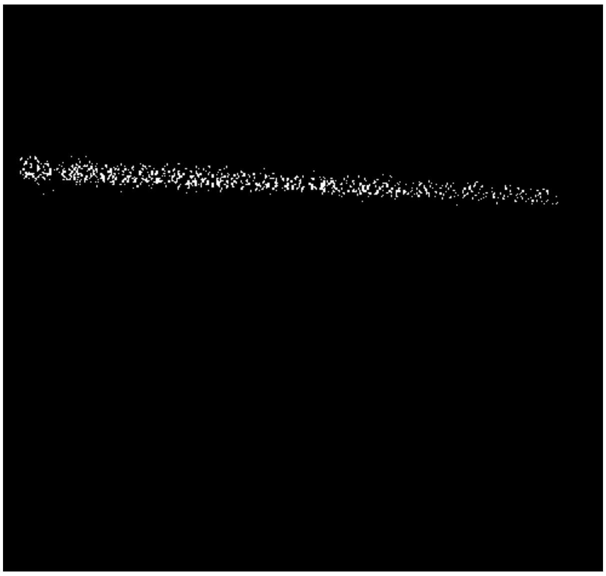

Figure 5. Processed image of the laser projection.

2.2 Measurement of dimensional and geometric deviations and surface roughness

Tool deflection is considered as the main cause of dimensional deviation of the milled width, as represented in Fig. 6. An Olympus SZ61 microscope was used to measure this parameter. A CCD camera connected to a computer captures the image visualized on the microscope and enables the user to measure the actual milled width using the software Image Pro Express. The software calculates the distance between two points, which are manually positioned. However, it is rather difficult to optically define the surfaces on which these points are lying, thus representing a source of measurement uncertainty. For each specimen, the average milling width was calculated from 15 measurements along the cutting path.

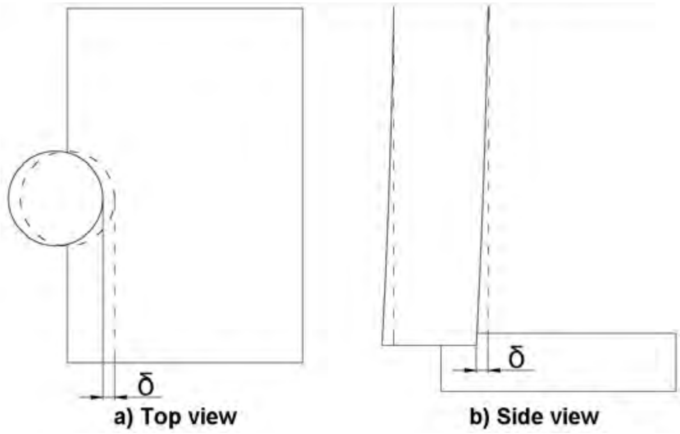

Figure 6. Dimensional deviation of the milled width.

A coordinate measurement machine Tesa Micro Hite 3D was used to measure the flatness of the surface generated by the secondary cutting edges, as indicated in Fig. 7. It calculates the flatness of a surface from 5 points with a resolution of 1μm and repeatability of 3μm. For each specimen, the surface flatness was measured 6 times and the average value was calculated.

In order to assess the surface roughness of the surface generated by the secondary cutting edges, the parameters R_a (arithmetic average height) and R_z (ten-point height) were measured with a Taylor Hobson Surtronic 25 portable roughness meter. Each parameter was measured four times for each cutting condition.

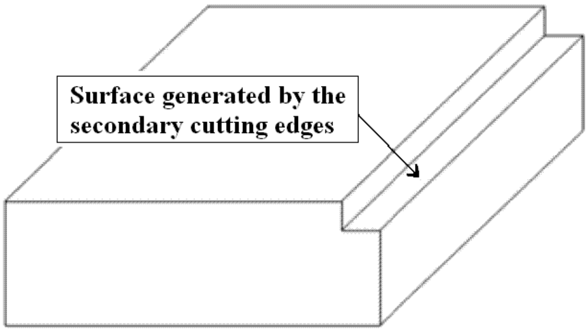

Figure 7. Surface generated by secondary cutting edges.

Flatness and roughness were assessed only on the surfaces generated by the secondary cutting edges owing to the fact that these were considered the surfaces of interest in the finished component. Furthermore, the small depth of cut values employed ($a_p =$ 1 and 2 mm) did not allow this evaluation to be conducted on the surfaces generated by the primary cutting edges due to the size of both the ruby probe used in the coordinate measuring machine and stylus head in the roughness meter.

3. RESULTS

Firstly, the results concerned with tool deflection are presented, followed by dimensional deviation (milled width), geometric deviation (flatness) and surface roughness. Finally, the relationship between the cutting parameters, tool deflection and the quality of the machined surface is discussed.

3.1 Tool deflection

As indicated in Tab. 1, six tests were performed with different combinations of the cutting conditions in order to evaluate the influence of each parameter (v_c, f_z, a_e and a_p) on tool deflection and on both dimensional and geometric deviations. The graph in Fig. 8 shows the results for the average cutting deflection.

As expected, the lowest value for tool deflection was obtained employing the lightest milling condition (test 1: v_c=60 m/min, f_z=0.05 mm/tooth, a_e=4 mm and a_p=1 mm), while the highest was recorded for the most severe condition (test 6: v_c=60 m/min, f_z=0.10 mm/tooth, a_e=8 mm and a_p=2 mm). It can also be seen in Fig. 8 that all cutting parameters

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present an appreciable influence on tool deflection and that depth of cut a_p appears to be the most influential one (test 5). This can be explained by the linear relationship between depth of cut and cutting force.

A two fold increase in cutting speed resulted in the elevation of tool deflection by approximately 50% (test 2). The same effect was observed when feed rate f_z and width of cut a_e were elevated (tests 3 and 4, respectively). The results for these three conditions were very similar and it is not possible to state which one is the most influential on tool deflection. Under all cutting conditions performed, tool deflection can be associated with the elevation of the radial force component and for this reason a decrease in tool deflection is not observed when cutting speed is elevated (in this case, a reduction in the tangential force component would be expected).

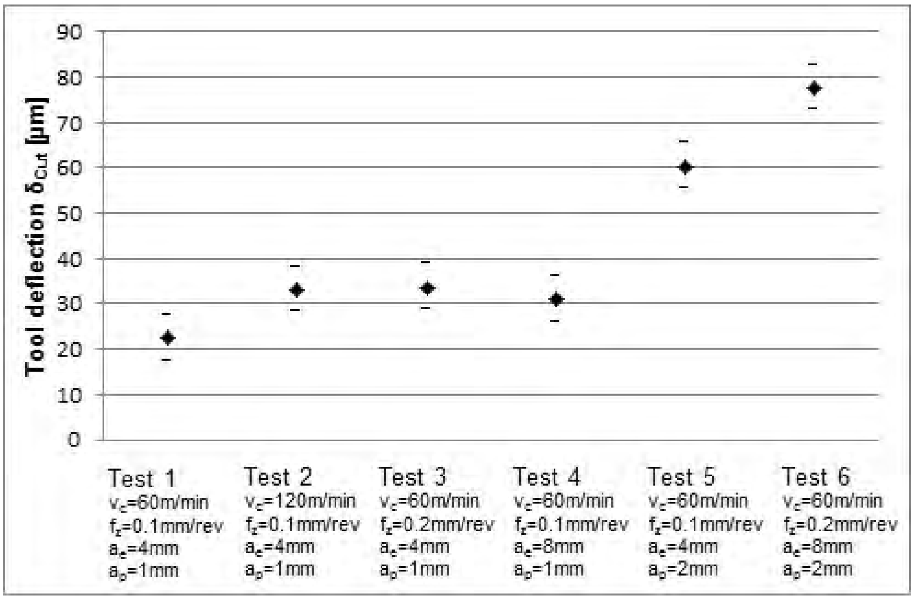

Figure 8. Effect of cutting conditions on cutting deflection δ_{Cut}.

3.2 Dimensional deviation

Figure 9 shows the results for dimensional deviation (milled width) considering the programmed width of cut. Thus, positive values indicate that the material removal was greater than the theoretical value, while negative values indicate that it was smaller. Increasing cutting speed (v_c) and depth of cut (a_p), see test 2 and 5, respectively, caused larger material removal than the nominal value. The same happened in test 6, the most sever milling condition. On the other hand, material removal was smaller than the theoretical value for test 3 (highest f_z value) and slightly smaller for test 4.

Surprisingly, under cutting conditions responsible for largest tool deflection (tests 5 and 6), the milled width was larger than the nominal value, i.e., material removal was higher than expected. Therefore, the results indicate that there are probably other factors besides tool deflection associated to the dimensional deviation. One possible explanation would be the thermal expansion of the workpiece induced by the increase in cutting temperature as the result of higher friction between the primary cutting edge and the workpiece as depth of cut is elevated: the cutting tool removes material while the workpiece expands, therefore the material removal is larger than the theoretical value. The difficulty in defining the surfaces used for the measurement of the actual milled width also contributes to the measurement uncertainty.

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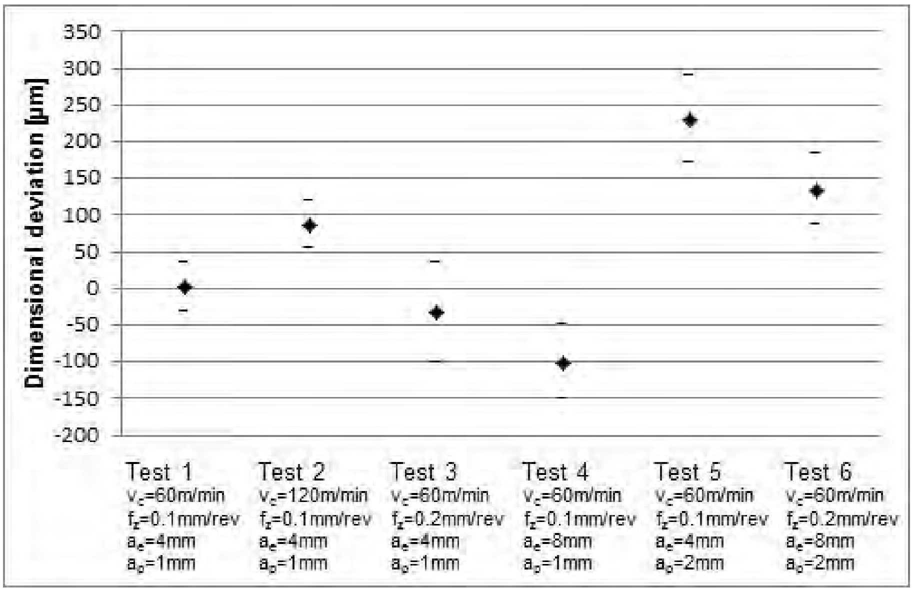

Figure 9. Effect of cutting conditions on dimensional deviation (milled width).

3.3 Surface flatness

The results for flatness of the surface generated by the secondary cutting edges are shown in Fig. 10. The maximum value of surface flatness is observed at the highest cutting speed. The elevation of v_c increases the workpiece temperature, which may be responsible for impairing flatness. The workpiece dimensions vary with temperature and, since milling is an interrupted cutting operation, the heat input oscillates periodically. Consequently more or less material is removed, featuring surface waviness.

Once the increase of temperature is responsible for the reduction of the cutting force due to a decrease in the material strength, the elevation of the flatness deviation can be associated with mechanical vibrations. By increasing spindle speed, the frequency that each tooth penetrates the workpiece may excite one of the natural frequencies of the system. With regard to chatter, there are no surface marks or other indication of its occurrence. Furthermore, the depth of cut used in the experiments was relative small, minimizing the risk of system instability. The other cutting parameters tested (f_z, a_e and a_p) had a smaller effect on surface flatness. Among them, depth of cut is probably the less influential.

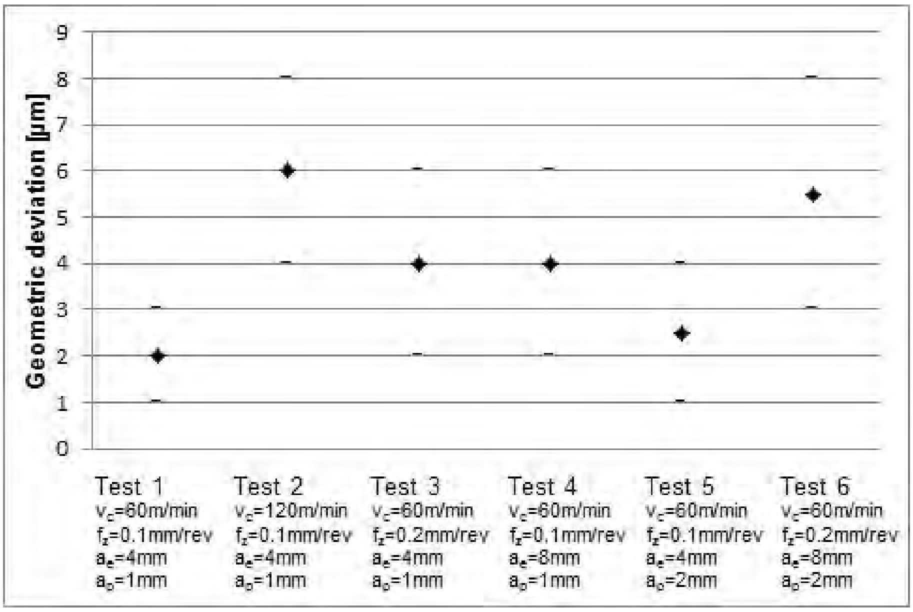

Figure 10. Effect of cutting conditions on machined surface flatness.

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3.4 Surface roughness

Figures 11 and 12 show, respectively, the results for the roughness parameters R_a and R_z measured on the surfaces generated by the secondary cutting edges under each condition. It can be noticed on the graphs that an increase in cutting speed reduces surface roughness as a result of cutting temperature elevation (reduction in the shear strength of the work material).

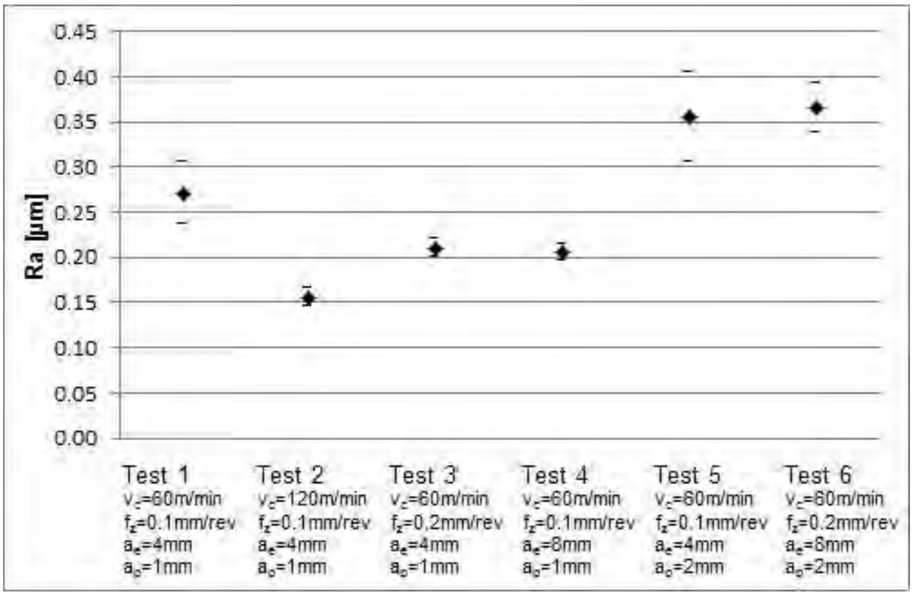

Figure 11. Effect of cutting conditions on surface roughness R_a.

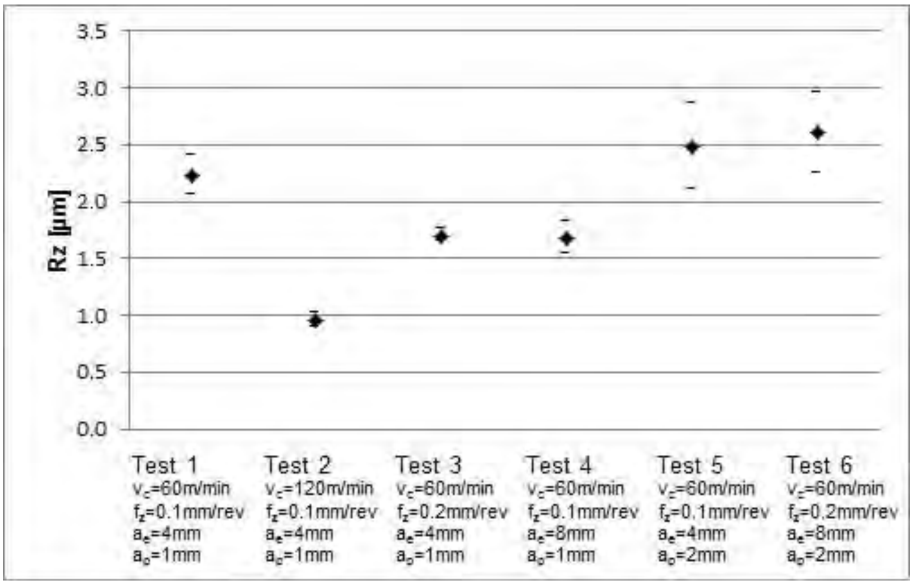

Figure 12. Effect of cutting conditions on surface roughness R_z.

Highest roughness values were recorded for tests 5 and 6, in which the cutting conditions were more severe. The cutting parameters which presented lesser influence on surface roughness were width of cut and feed rate. This was not unexpected owing to the fact that roughness was measured on the surface generated by the secondary cutting edge.

3.5 Relation between tool deflection and surface quality

Table 2 presents a qualitative comparison of the influence of the milling parameters (v_c, f_z, a_e and a_p) on tool deflection and surface quality. The arrows pointing up indicate the variation of the cutting condition caused an increase on the analyzed parameter, while arrows pointing down indicate the opposite trend.

Table 2. Results summary.

	Tool deflection	Dimensional deviation	Surface flatness	Surface roughness
v_c	↑	↑	↑	↓
f_z	↑	↓	↑	↓
a_e	↑	↓	↑	↓
a_p	↑	↑	↑	↑

It can be seen in Tab. 2 that the milled width value does not correspond necessarily to the tool average cut deflection. Although the variation of all cutting parameters brought an increase on surface flatness, there is no clear relationship between tool deflection and flatness and roughness of the surface generated by the secondary edges. In both cases, tool deflection occurs in a plane normal to the analyzed surface.

The variation on cutting speed has a negative effect on tool deflection, dimensional deviation and flatness, although it presented a positive effect on surface roughness. Feed rate and width of cut have a similar influence on all analyzed parameters, even in magnitude; being roughness the least affected.

The increase in depth of cut has a negative effect on all analyzed parameters: tool deflection, dimensional and geometric deviations values were maxima with the elevation of this parameter. In all aspects, this appears to be the most critical cutting parameter.

4. CONCLUSIONS

The proposed method allows tool deflection measurement during milling with reasonable accuracy. It is a simple technique, which results can be used for comparative purposes depicted in this paper. In order to increase the accuracy of the system and minimize errors, better positioning of the components must be carried out. The principal advantages of this method are the low cost and simplicity and the main drawback is associated to the discrete signal acquisition, which makes it impossible to analyze the temporal function of tool deflection as well as its behavior. Another disadvantage of the proposed system is the sensitivity to external factors, therefore, calibration is required every time that the position of the elements is altered.

All cutting parameters investigated (v_c, f_z, a_e and a_p) affected tool deflection due to their influence on the radial component of the milling force, however, depth of cut a_p was found to be the most influential.

The dimensional deviation (milled width) was not found to be directly related to tool deflection. Therefore, it can be assumed that there are other external factors that affect the milled width, probably thermal effects involved in the process.

The geometric plane in which tool deflection occurs is perpendicular to the one generated by the secondary cutting edges. As a consequence, the results show no straightforward relationship between tool deflection and the quality of this surface.

Finally, lowest surface roughness was obtained employing high cutting speed together with low feed rate, depth of cut and width of cut. Any other combination of the cutting parameters was detrimental to surface roughness.

5. ACKNOWLEDGEMENTS

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