INFLUENCE OF HIGH PERFORMANCE CUTTING OPERATIONS ON THE RESIDUAL STRESSES OF ALUMINUM STRUCTURAL WORKPIECES

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Abstract

Machining operations on aluminum structural parts are typically carried out under high performance cutting conditions, which comprise high feeds, depths of cut and cutting speeds. These machining conditions exert thermal and mechanical loads on the workpiece, which lead to changes in the subsurface material. Residual stress is a manifestation of these machining induced changes. Its economical importance is considerable, since it can lead to high rejection rates as a consequence of part distortion. Therefore, it is important to know the influence of the machining process on residual stress. This paper presents the results of investigations about the influence of the cutting speed and feed per tooth on part distortion of workpieces made out of forged aluminum alloys.

1 Introduction

The development of machines and cutting tools has enabled very high material removal rates through the technology known as high performance cutting (HPC). This possibility offers an efficient solution for manufacturing of thin monolithic components. The advantage of high performance cutting in comparison to conventional milling processes are very high feed speeds by high cutting rates, which enable significantly reduced production times [1, 2].

An efficient and flexible manufacturing process is a requirement in the aerospace industry in order to cope with the market unpredictability. This requirement, together with the need to reduce fuel consumption, has led to the design of thin monolithic components. Generally, such components are produced out of a single prismatic aluminum block in order to avoid huge stocks of preformed parts and additional weight due to fixture components like bolts, screws and pins. Therefore, up to 95% of the volume of the raw material has to be removed through machining processes [2, 3].

In the last few years the research work has focused on accomplishing these extremely high material removal rates. However, the influence of these production processes on the properties of these manufactured components has not been sufficiently investigated. The relationship between the process variables, e.g. cutting parameters, tool geometry and cooling strategy, and the introduction of residual stresses during machining operations has not been completely understood [4].

The residual stress state of a workpiece can significantly extend or shorten its lifetime. Furthermore, part distortion is a function of residual stresses and is caused by complex relationships between material processing, component design and manufacture. Residual stresses become important with respect to part distortion especially for thin monolithic aerospace components. [5].

Residual stresses can be defined as mechanical stresses in a solid body, which is currently not exposed to forces or torques and which has no temperature gradient [6]. They can be attributed to mechanical and thermal loads, which both appear during machining processes interdependently [7, 8, 9]. Mechanical loads mainly result in compressive stresses and

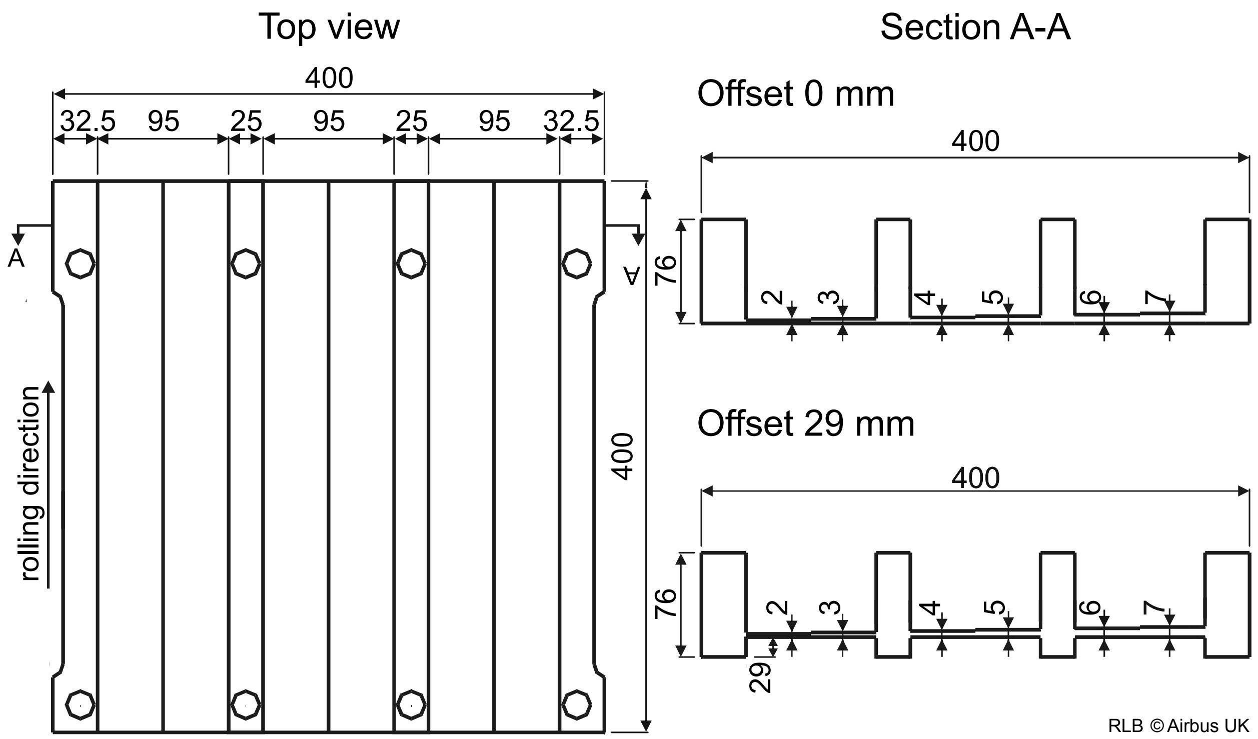

Fig. 1. Workpiece geometry

thermal loads in tensile stresses in the materials subsurface. The combination of both determines the final residual stress state of the workpiece [10, 11].

Modifications of the machining process can significantly control the final residual stress state, due to their direct influence on the mechanical and thermal loads [12, 13]. On the one hand, the mechanical loads exerted by the forces on the workpiece lead to the generation of compressive residual stresses. On the other hand, rapid cooling of the very hot contact zone causes a shock on the superficial workpiece layers, which lead to tensile residual stresses. For this reason, it is fundamental to measure separately both, the mechanical and thermal loads, and to relate them to the machining parameters. This enables the analysis of the machining process as a system according to its influence on the final residual stress state.

Research has been carried out in order to find the relationship between the machining process and residual stresses. Plöger investigated the influence of high speed cutting on the residual stresses in turning of AISI 1045, while Gey researched the influence of the cutting parameters on the residual stresses in end milling of TiAl6V4 [11, 13]. However, there is limited knowledge on the effect of machining processes on residual stress in aluminum alloys [14]. Therefore, a comprehensive study of the influence of machining conditions on residual stresses in high strength aluminum alloys is much sought after in the manufacture of large and thin monolithic aerospace components. Furthermore, the prediction of residual stresses is until now only qualitatively possible. The necessary knowledge is not available, in order to predict the values of the residual stresses and ultimately the distortion of the workpieces after machining [11].

2 Experimental Procedure

Side milling tests were carried out on Al 7449 T7651 at two different workpiece geometries, as shown in Fig. 1. The dimensions of the workpieces are 400 x 400 x 76 mm. Both workpiece geometries were machined out of prismatic aluminum blocks, with an original symmetrical residual stress distribution within ± 15 MPa. After the machining, four bars with the full original thickness (76 mm) remain.

test number	cutting speed v_c [m/min]	feed per tooth f_z [mm]	cutting depth a_p [mm]	cutting width a_e [mm]	offset [mm]
1	500	0.15	5	20; 14; 13.5	0
2	1250	0.20	5	20; 14; 13.5	0
3	1500	0.20	5	20; 14; 13.5	0
4	500	0.15	5	20; 14; 13.5	29
5	1250	0.20	5	20; 14; 13.5	29
6	1500	0.20	5	20; 14; 13.5	29

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Tab. 1. Cutting parameters

In each workpiece 6 steps of different thickness (2 - 7 mm) and a width of 47.5 mm are located between these four bars. The difference between both workpiece geometries consists in the offset off the ground. In the first case, the location of the ground coincides with the original rolled surface (offset 0 mm). In the second case, the distance between the ground and the original rolled surface amounts to 29 mm.

The applied cutting parameters are shown in Tab. 1. All tests were performed with coolant in a machining centre Heller MC16. The workpieces were prepared with a milling head. The final cut has a constant cutting depth of $a_p = 5$ mm and has been made in three steps with cutting widths of $a_e = 20$, 14 and 13.5 mm. The cutting parameters used for the preparation of the workpieces were kept constant in order to avoid any influence on the final result. The last cut was carried out with a cemented carbide tool with a diameter of $D = 20$ mm, a length of $L = 145$ mm and a helix angle of $\delta = 45°$. All final cuts were carried out with sharp tools in order to avoid any effect due to tool wear.

After machining the workpiece geometry was measured with a precision coordinate measuring machine [CMM] of the type PMM 866 by Leitz. This device possesses a measurement uncertainty of (1.4 + L/300) µm. The measurements were taken at the upper side parallel to the direction of cut on the centerline of each of the six steps. Further measurements were taken at the lower side of the workpieces perpendicular to the direction of cut in order to quantify the curvature of the whole workpiece.

Following these measurements, the strips were separated from the original workpieces. Additional measurements were carried out with the CMM at each of the single strips after the separation.

3 Experimental results

A dependency of the part distortion on the machining parameters has been observed. Fig. 2 shows the form deviation of the workpieces as a function of the strip thickness and the cutting speed. The form deviation is defined as the greatest vertical distance between two points within the measured profile.

Each side of Fig. 2 shows the form deviation of workpieces with an identical geometry but machined at different cutting speeds. The results on the left side correspond to the workpieces with an offset of 0 mm, those on the right side to an offset of 29 mm.

As expected, the form deviation decreases by an increasing strip thickness. Since the cutting parameters are kept constant within a workpiece, it can be assumed that the influence of the machining operations on the properties at the subsurface area is equal for all the machined strips in a single workpiece. These effects are independent from the strip thickness. The different form deviation as a consequence of a change in the strip thickness is caused by the distinct mechanical resistance due to the diverse cross sections of the strips.

Furthermore, an increase of the cutting speed from $v_c = 1250$ m/min to $v_c = 1500$ m/min

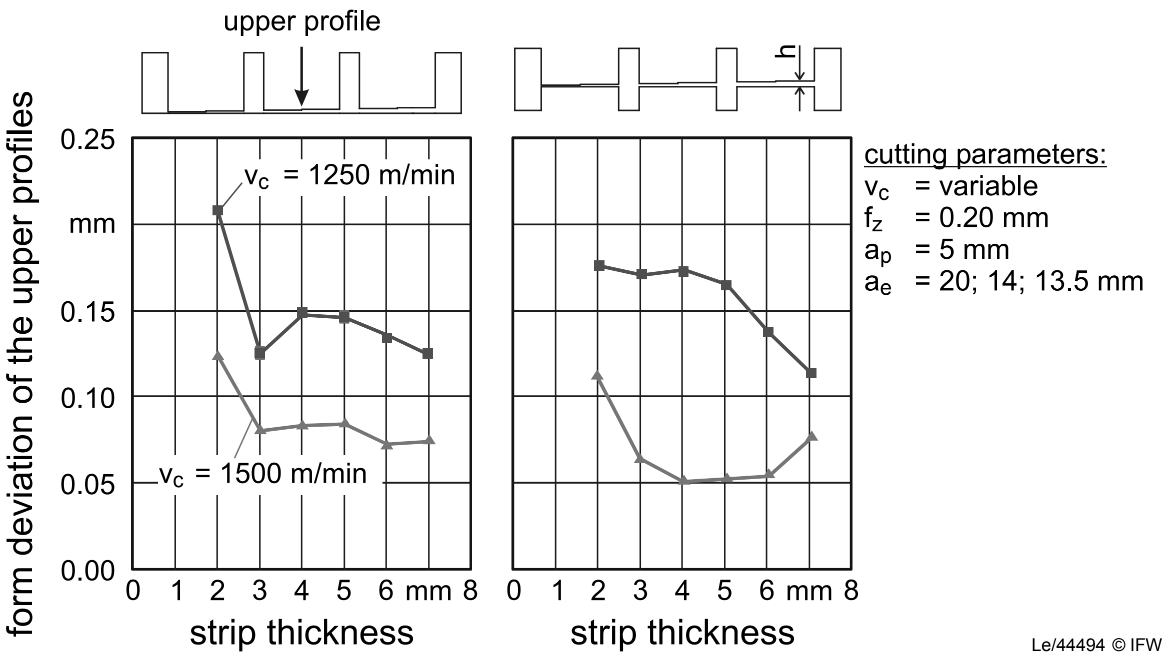

Fig. 2. Form deviation by different machining parameters

leads for both workpiece geometries to the lowest form deviation.

A closer analysis of the profiles of the steps provides further information in order to evaluate these observations. Fig. 3 shows the profile of the strips of two workpiece geometries machined at different cutting conditions, all other parameters being constant, e.g. step geometry, cutting tool and cooling. In analogy to Fig. 2, the left side shows the results for workpieces with no offset, the right side those of the workpieces with an offset of 29 mm.

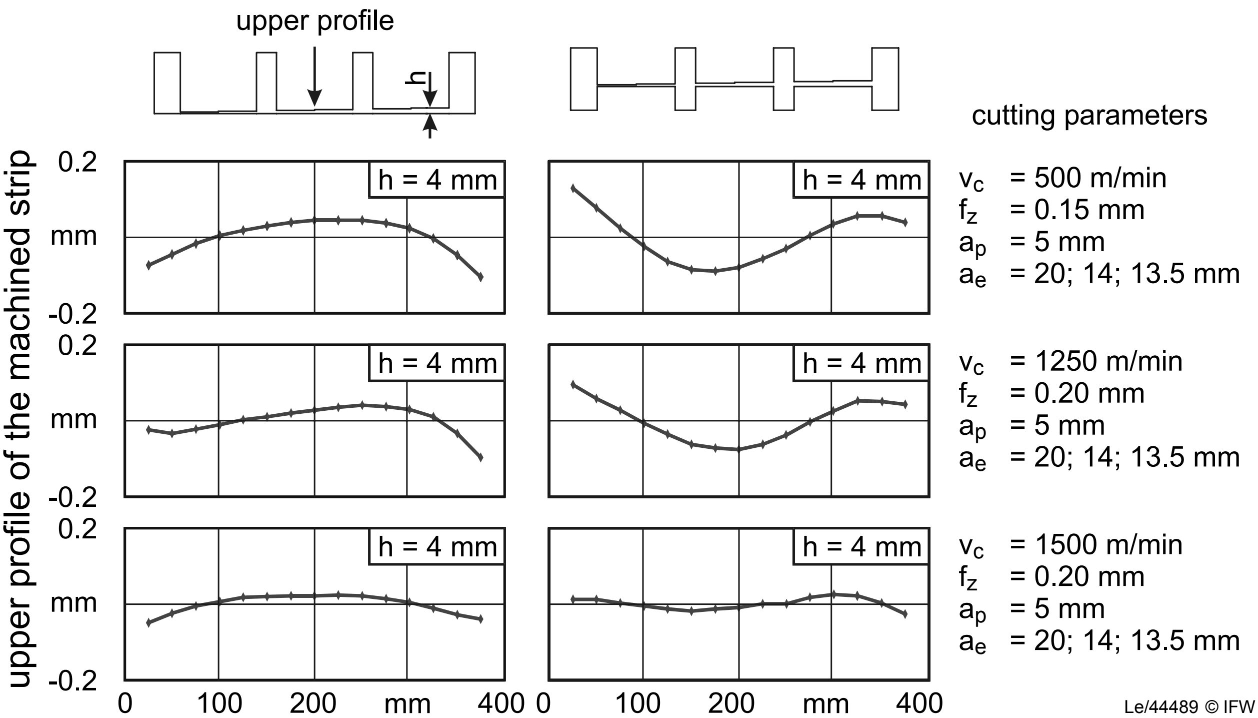

Fig. 3. Strip profile by different machining parameters

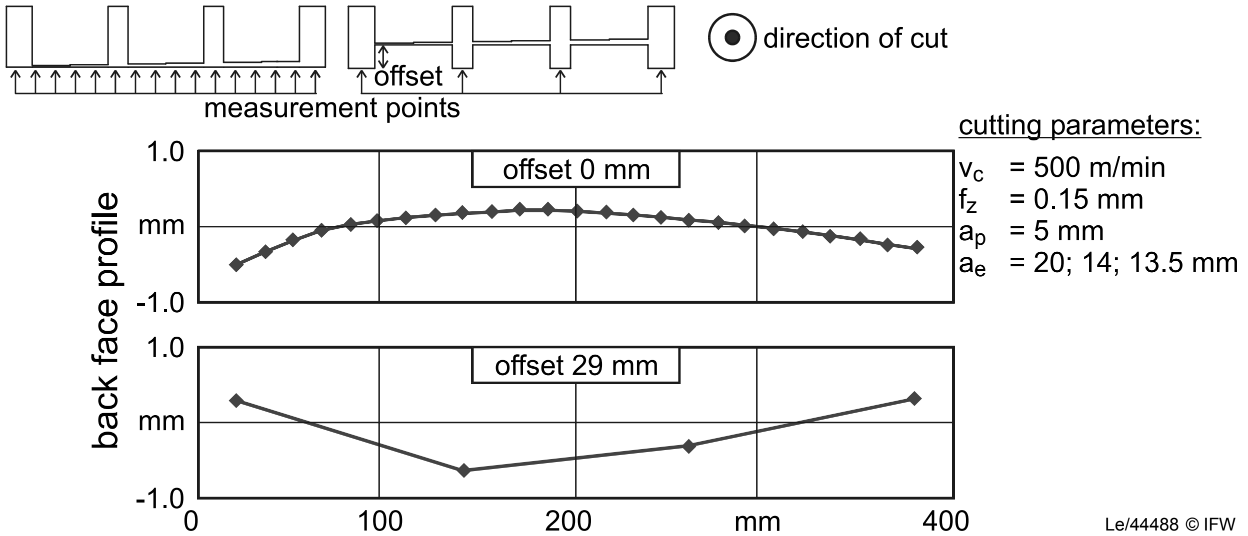

Fig. 4. Back face geometry by different workpiece geometries

At the first sight it is evident that the workpiece geometry possesses a significant influence on the overall profile of the workpieces. Under these experimental conditions, workpieces with no offset show a convex profile, whereas workpieces with an offset exhibit a concave profile. This observation is independent of the machining parameters.

The convex profiles denote a part distortion due to compressive residual stresses in the upper subsurface. The concave profiles of the workpieces with an offset of 29 mm are caused by tensile residual stresses in the upper subsurface.

However, a certain influence of the machining parameters on the part distortion can also be observed. For both workpiece geometries, the lower cutting speeds lead to a more pronounced curvature of the distorted part. A further increase of the cutting speed leads to a flattening of the profile. These facts are in accordance with the results shown in Fig. 2. Assuming an identical residual stress distribution previous to machining in all aluminum blocks, only the differences between profiles with the same workpiece geometry, but machined at distinct cutting conditions provides information about the influence of the machining operations.

The influence of the workpiece geometry on the overall part distortion can be seen in Fig. 4. The upper curve corresponds to a workpiece with no offset and the lower curve to one with an offset of 29 mm. Both workpieces have been machined under identical cutting conditions. The profiles at the back side perpendicular to the direction of cut also show a convex form at the workpieces with no offset and a concave form at the workpieces with an offset.

As presented in the experimental design, the strips have been separated from the whole workpieces after the first measurements. After the separation the single strips suffer a considerable additional deformation without the constraint of the rest of the workpiece. Fig. 5 shows the form deviation of the single strips. These measured values are significantly higher than in the case of the whole workpieces. Both diagrams show clearly that the form deviation decreases by an increasing strip thickness. This observation corresponds to the expectations. The reason for it has already been discussed for the whole workpieces.

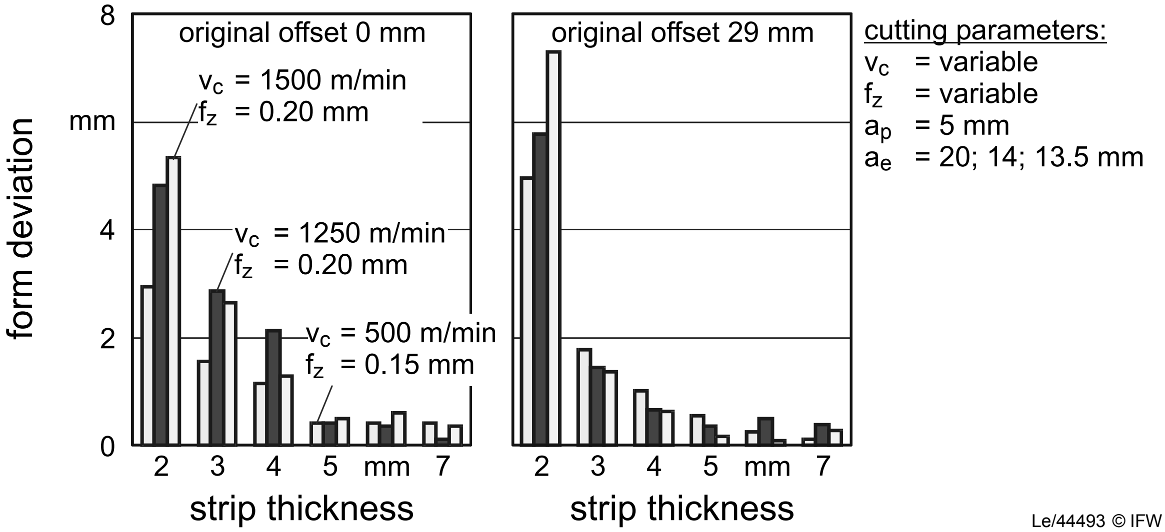

Fig. 5. Form deviation of the separated strips by different cutting parameters

The results do not show however in this case a consistent influence of the cutting parameters on the form deviation. On the one hand, the highest form deviation is measured on the strips with a thickness of h = 2 mm machined at the highest cutting speed of v_c = 1500 m/min. On the other hand, the lowest form deviation for the strips with this thickness is observed at those machined with the lowest cutting speed of v_c = 500 m/min. These results contradict the obtained values for the whole workpieces shown in Fig. 3.

The final profile of the strips after the separation from the whole block is shown in Fig. 6. The main shape of the strips as a consequence of the offset of the workpieces can be still observed after their separation. A workpiece machined at the rolled surface exhibits a convex shape. Workpieces produced in a depth towards the middle of the blocks present a concave shape.

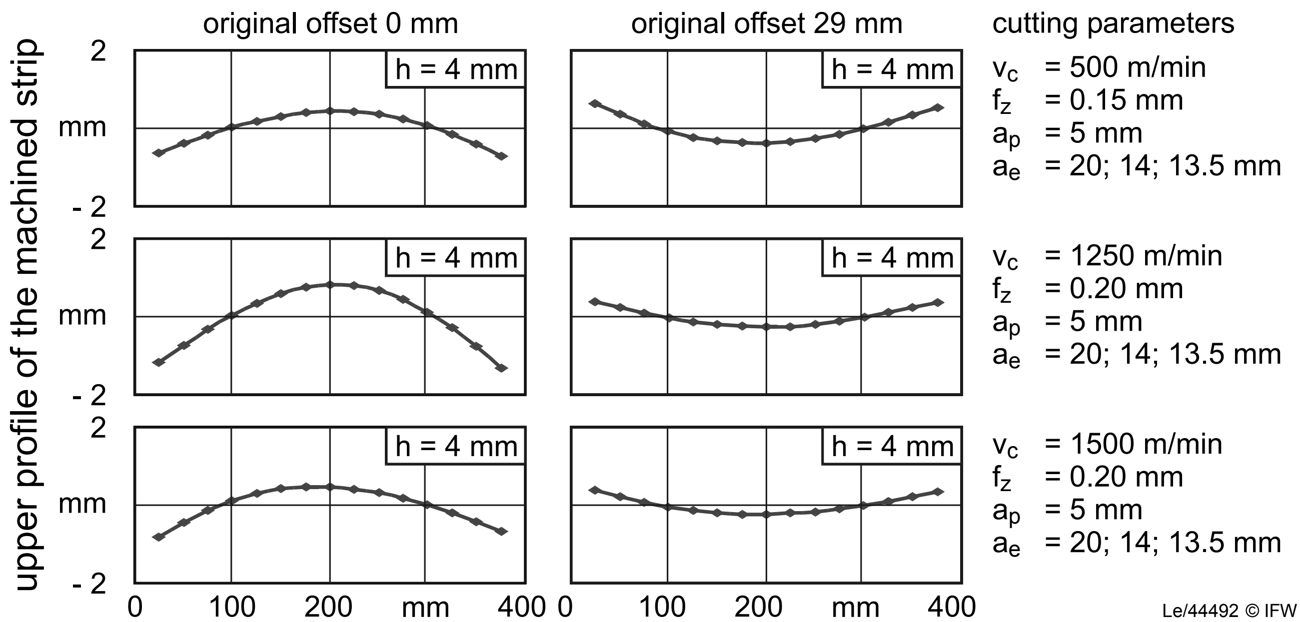

Fig. 6. Profile of the separated strips by different cutting parameters

4 Conclusions and outlook

This study shows a very strong influence of the material manufacture and workpiece geometry on part distortion. The combination of both factors leads to convex profiles for the workpieces with no offset and to concave profiles for the workpieces with an offset of 29 mm.

The material manufacture, material removal and workpiece mechanical properties lead to the different step profiles of the workpieces with distinct geometries, though the workpieces were machined under the same cutting conditions.

The influence of the machining process on part distortion can be studied by the analysis of the profiles of workpieces with an identical geometry, which were machined under different cutting conditions.

It has also been shown that the cutting process does have a significant influence on part distortion. Both workpiece geometries, i.e. offset of 0 mm and 29 mm, exhibit the lowest part distortion after being machined with the highest cutting speed. This implies that the machining plays a role on part distortion. However, this tendency cannot be confirmed after the strips have been separated from the whole workpieces.

Part distortion is a consequence of the superposition of the residual stress due to the material manufacture, material removal and machining operations, combined with the workpiece mechanical properties, which are mainly defined by its material and geometry.

Future work will focus on the exact influence of machining on residual stresses. Very robust workpieces with sufficient thickness will be machined, in order to avoid any part distortion and to enable an accurate quantification of the residual stresses.

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