Investigations on the influence of local material properties of Burr Formation

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Abstract
The modern manufacturing has high demands on the cutting process. Today, the precision of the arising workpiece and the by-products of the machining process are one of the main parts of research. Burrs are some of the by-products. They result from the deformation of the workpiece material near the workpiece edge caused by the forces of the cutting process. The removal of this by-product requires a big partial amount of the manufacture costs. Fraunhofer Institute for Machine Tools and Forming Technologies deals with a new valuation of burr reducing.

1 INTRODUCTION

In the metal-cutting manufacturing the nuisance adhering residual material is called burr [1]. Burr is based on a deformation process in front of the cutting tool during the metal machining. The area in front of the cutting edge is also called primary shear zone. It is characterized by the shear plane and the high deformation rates within. In general the shear plane forms itself between the cutting edge and the nearest undeformed workpiece surface. This state is typical for the cutting far from the workpiece edge. When the tool comes near the edge of the workpiece the primary shear zone switches to the burr shear zone. The burr shear zone arises between the tool edge and the so called pivot point of the burr. Around the pivot point (P) the workpiece material rotates during the burr formation. In the next figure (Figure 1) the geometry of the burr is defined.

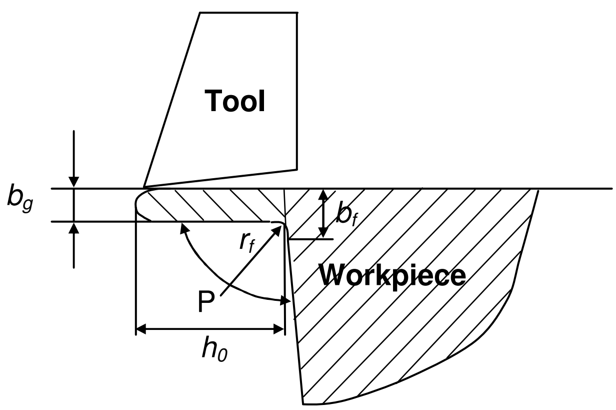

Figure 1: Geometry of the burr [1].

The burr shear zone is the most important deformation zone during the burr formation. It has a wide influence on the form, the height and the stiffness of the burr. Furthermore there is an influence on the burr shear zone, for example the geometry of the tool, the cutting parameter and the material of the tool and the workpiece. Especially the workpiece material has an important influence on the burr formation. Ductility of the material is the most important material property. Beier [2] clarifies in his formula for the burr affinity N that the elongation without reduction of the cross-sectional area ε_{gl} and the tensile strength R_m are the most important factors. Another formula for burr affinity N from Link [3] includes the strength $R_{p0,2}$, the yield strength A and tensile stretch Z, but all including parameters dependent on the material ductility.

$$N_{Beyer} = \varepsilon_{gl} \cdot R_m \text{ [2]} \tag{1}$$

$$N_{Link} = (R_m - R_{p0,2})(A + Z) \text{ [3]} \tag{2}$$

Concluding, there is a direct coherence between the ductility of the workpiece material and the burr formation.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Materials Basis

According to Beyer's and Link's researches it is possible to reduce the burr affinity with a reduction of the workpiece ductility. So it must be able to create a burr minimisation with the modelling of the workpiece material.

For the manufacturing of high quality parts often steels are used, especially heat-treated steels. A commonly used material is C45E, which is the test material in this work.
Reducing the ductility of this kind of steel is possible with hardening without tempering. The tempering process, which is used mostly after hardening, increases the ductility again.
Machining of hardened parts has disadvantages. The added strength increases the cutting force and the wear on the tool. To avoid this, the hardened workpiece volume must be reduced to a minimum. Burr formation appears mostly on the tool exit, which is mostly the workpiece edge. Therefore it is useful to harden only the workpiece edge.
To obtain a minimum volume of hardened material and a local material modelling often the surface hardening is used. Laser hardening is heat treatment with the minimum of modelled material. The laser allows a very local high heat input.
To have a relation between the depth of hardening and burr formation the laser hardening and the induction hardening are tested. The induction hardening is an often used heat surface treatment with a higher depth of hardening than laser hardening.

2.2 Hardening Treatments

The purpose of the hardening is the reduction of ductility in the burr formation zone, which is also called burr shear zone. Hashimura [4] showed in his analyses how the deformation zone is formed during burr formation.

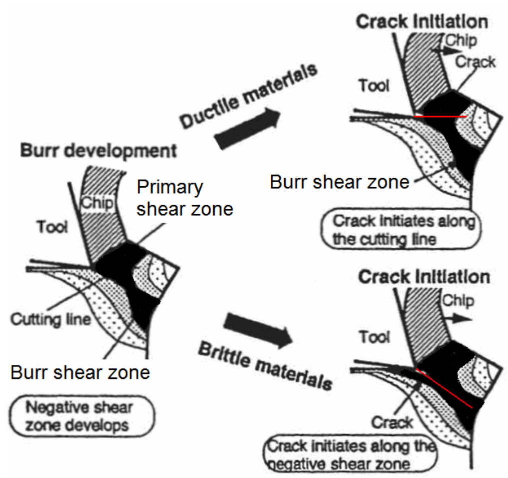

Figure 2: Deformations during burr formation [4].

He showed that a rotation of workpiece material around the so called pivot point is the mechanism of the formation. The highest deformation appears in the burr shear zone.

If the strain in this area rises up over the ultimate strain a crack initiates along the burr shear zone. If the strain stays under the ultimate strain in the burr shear zone the crack runs along the tool path. In the first case, where the burr runs along the burr shear zone, the usually positive burr like in Figure 1 switches to a so called negative burr. Pekelharing [4] detected this kind of burr in 1978.

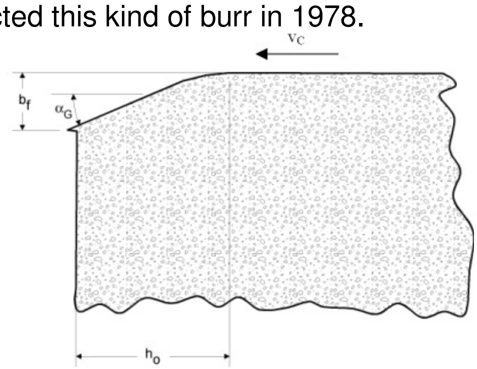

Figure 3: Geometry of the negative burr.

The structure of the negative burr is nearly similar to a trimmed edge. However, it has a so called secondary burr, which is smaller but has the same negative properties. The goal is to avoid this secondary burr with the help of material modelling as well.
It is clear that the hardening must be located in the burr shear zone and in the formation area of the secondary burr.
Researches about surface hardening show the difference between the laser hardening and induction hardening. There are high varieties for the hardness distribution between both. In the following pictures the bottom left corner is the tool exit edge.

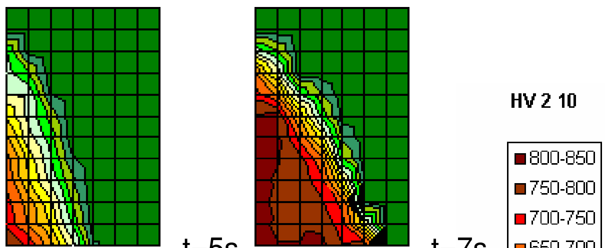

Figure 4: Hardness distribution for induction hardening.

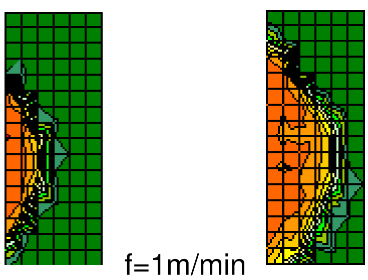

Figure 5: Hardness distribution for laser hardening.

Laser hardening has a well lower depth of hardening than induction hardening. The depth of hardening for laser hardening is, depending on the laser feed, between 0.8 and 1.35mm. For induction hardening it depends on the induction time and it is between 2.1 and 3.3mm.

Similar to the depth of hardening there are great varieties for the maximum of hardness. In the case of induction heating the measured maximum hardness was 845HV2. For laser hardening it was only 703HV2. The logical conclusion is that the lower maximum hardness by laser hardening is based on an uncompleted martensite transformation. The reason for this is the lower cooling rate for the field of lower temperature in the cooling process. In the case of laser hardening the so called self determent was used. By self-quenching the cold area around the localized hot area quenches that small hot area. A high heat conductance and a high temperature difference are essential. During the cooling the surrounding areas heat up and the temperature difference drops. Following, the cooling rate goes down and the martensite transformation stops. As a result the material structure has a high part of the so called residual austenite. With the part of the residual austenite the ductility rises up as well.

For the realisation of the tests 4 different hardness distributions (Figure 4 and 5) were tested. For each hardness distribution 5 similarly test items were manufactured and machined, to get a verified output for the burr formation by this heat treatment.

2.3 Machining Experiment

Complementary to the machining experiment a FEM simulation should be made. The simulation should affirm the deformations during the burr formation. DEFORM™2D will be used for the simulation of the machining operation. The 2D character of the simulation makes demands on the experiment. In the 2D simulation of cutting process most times the so called orthogonal cut is used as a simplified model. In this model no expanding of the material in the depth (z axis) exists. For the comparability between the simulation and the experiment, the experiment must have a 2D character without a chip expanding in the depth. To realize this specification the turning of a flute was used. By this machining process the tool moves straight radial into the rotating workpiece. The expanding of chip material in axial direction is blocked by the side wall of the flute.

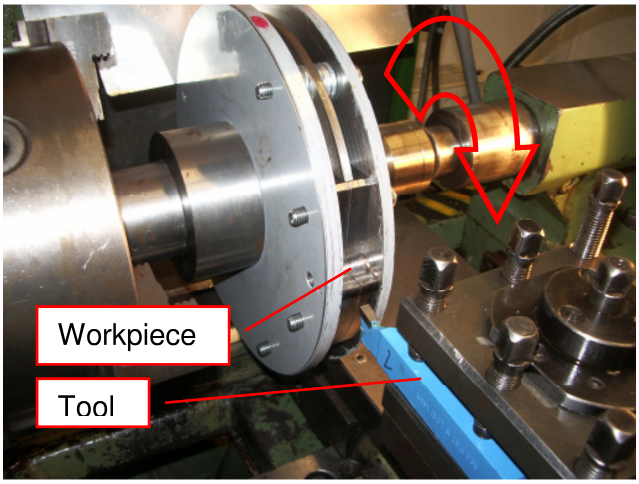

Figure 6: Experimental setup.

For a cutting process, one as elementary as possible, it was necessary to use a simple cutting tool. It was without chip former and chip breaker.

2.4 Results of the Experiment

The experiment was divided into a test of

- 5 untreated workpieces,
- 5 laser low hardened workpieces,
- 5 laser high hardened workpieces,
- 5 inductive low hardened workpieces, and
- 5 inductive high hardened work-pieces.

First the untreated workpieces were tested of the burr formation. After testing, the geometries of the burr were measured with a light optical microscope. For the rating of the burr the geometries were summarized in the following formula (3) for the burr value. The formula is based on a formula from Link [3], but it is specially adjusted for comparing different kinds of burrs.

$$G_{red} = \frac{4b_f + h_0}{4} \tag{3}$$

The burrs of untreated workpieces had an averaged burr value of 314µm. In the following figure are some REM pictures of a typical burr.

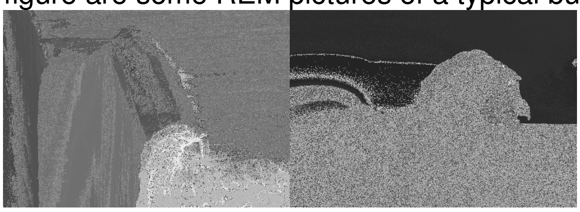

Figure 7: Burr by untreated workpiece.

The burr formation by the heat treated workpiece was very different. There is a big influence of the hardened zone on the burr formation. Laser hardening reduced the burr to a burr value of 159µm for the workpieces with the high depth of hardening and a burr value of 98µm for the workpieces with the low depth of hardening. In the case of laser hardening the burr has the image of the negative burr with a secondary burr, which was described by Pekelharing (Figure 3).

With the inductive hardening of workpiece edge the burr avoidance was reached. A negative burr without a secondary burr was build by the inductive hardened workpiece. In the following figure 8 is a REM picture of the negative burr. The burr face has the typical crystalline structure of a brittle fracture.

Figure 8: Burr of inductive hardened workpiece.

Based on the negative burr geometries the burr value is also negative. The workpiece with a low depth of hardening by the inductive burrs has a burr value of -207µm and the workpieces with a high depth of hardening a value of -389µm. In comparison to the burr values of the laser hardened workpiece the influence of the depth of hardening is different. By the inductive workpiece the burr value falls with the rising of the depth hardening. In case of laser hardening the burr value rises with the rising of the depth of hardening. Concluding, the depth of hardening has no or only a small influence on the burr formation. The other difference between laser hardened workpiece edges and inductive hardened edges was the maximum hardness. The maximum hardness of the inductive hardened workpieces was around 840HV2 and for the laser hardened ones only around 700HV2. Together with the burr value for the untreated workpiece with hardness around 250HV2 we get the following schema.

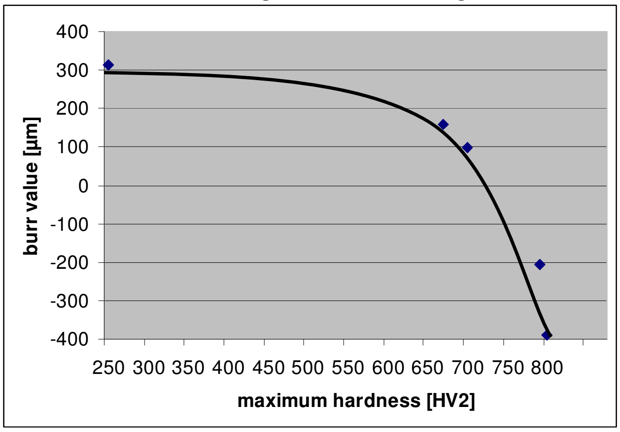

Figure 9: Influence of the maximum hardness on the burr formation.

Like Figure 9 shows, there is a direct influence from the maximum hardness and the burr value. With the rising of the hardness the burr value falls. But the hardness is not the important value. The ductility, which falls with rising hardness, is the important value. Another sign for the direct influence of the ductility on the burr formation is the structure of fracture surface by the inductive hardened workpieces. The crystalline structure of the fracture surface is a result of fracture in material with a very low ductility.

Concluding, with the hardening of the workpiece edge it is possible to reduce the burr. With inductive hardening a higher hardness is possible, which causes a lower ductility. When the ductility falls below a specific value a burr free cutting is possible. This effect is based on a brittle fracture along the burr shear zone.

3. NUMERICAL INVESTIGATIONS

3.1 Simulation Setup

The goal of the simulation in this work is to investigate the deformation and mechanism during the burr formation on a hardened workpiece edge. For the realization of the simulation the FEM program DEFORM™2D V9.0 was used.

The simulation of burr formation of untreated uniform material workpieces is common, but in this case normal material and a treated material part exit in one workpiece. This means that the workpiece has two different kinds of material with a direct contact with the tool during the machining. The first test with two ideal sticking workpieces was a failure, because the “glue line” scarifies during the remesh processes. Another option was to change the material parameter of several mesh elements in the workpiece mesh. In DEFORM™2D V9.0 the use is able to change parameters for several elements. One of those is the material. It is able to change the material in the zone of hardened material like in the experiment workpiece. But in DEFORM™ only a normalized C45-steel exists. The user creates new material, implements all the material properties for it and creates a suitable fracture criteria. In the next figure, Figure 10, the simulation workpiece and tool are shown. The red material is the normalized steel and the blue one is the hardened steel.

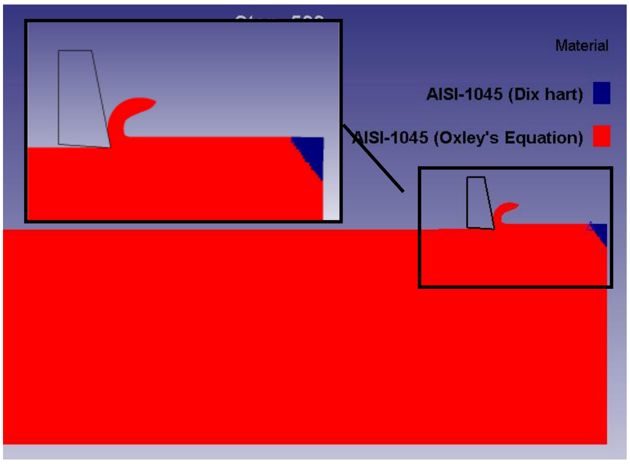

Figure 10: Simulation setup.

The cutting parameters, like cutting speed and cutting depth, were identical to the experiment. For comparison a simulation with a hardened workpiece edge and a simulation with a uniform material were made. In the following text the author dwells more on the simulation of the machining of the hardened workpiece.

3.2 Steps of Burr Formation

Based on the researches of Hashimura [4] the burr formation can be divided into eight phases. In the following text each figure consists of two simulation pictures. The picture on the left side is without heat treatment and the one on the left with a hardened workpiece edge.

Phase 1 – Continuous cutting

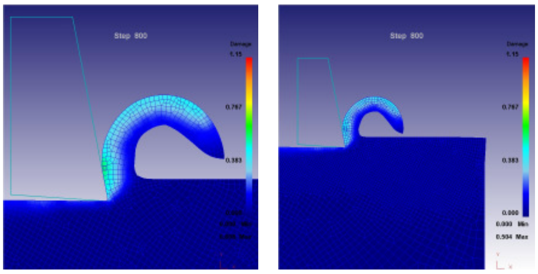

Figure 11: Phase 1 of the burr formation.

In the first phase of the burr formation there are no varieties between the treated and the untreated workpiece. The tool is far away from the workpiece edge and the typical primary shear zone occurs in front of the tool edge.

Phase 2 - Pre-Initiation

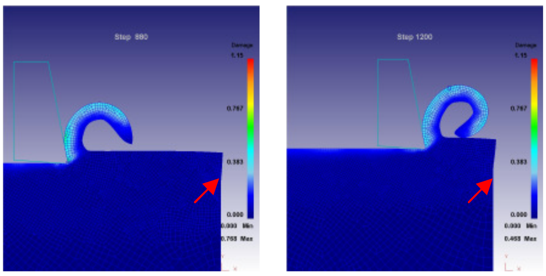

Figure 12 - Phase 2 of the burr formation.

Phase 2 is the first phase with a deformation of the workpiece edge. A rotation of the upper workpiece edge around the so called pivot point (Figure 1 and red arrows) begins. Varieties for the initiation time between the hardened and the untreated workpiece exist. The pre-initiation by the hardened is earlier.

Phase 3 - Initiation

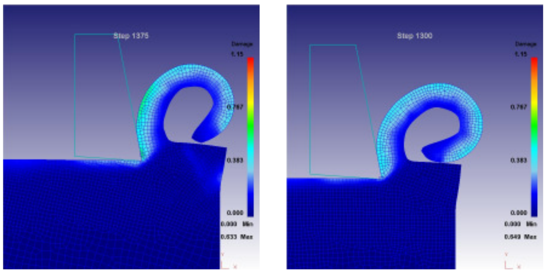

Figure 13 - Phase 3 of the burr formation.

With the initiation of the burr formation a new deformation zone evolves. The primary shear zone reshapes to the so called burr shear zone. This zone is located by the untreated workpiece between the tool edge and the pivot point.

Phase 4 - Pivoting

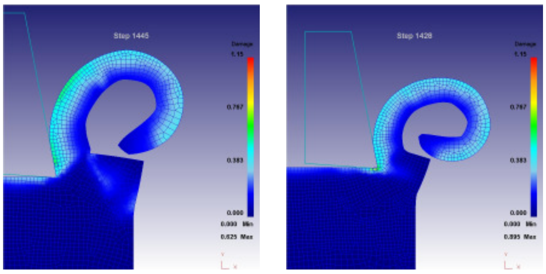

Figure 14 - Phase 4 of the burr formation.

In the fourth phase the rotating speed of the workpiece edge around the pivot point arises. The deformations in the burr shear zone by the treated workpiece are much higher than in the untreated one. Also the deformation zone in the treated workpiece is removed. The shear zone is not between the pivot point and the cutting edge. It is located along the boarder between the hardened and the soft material.

Phase 5 – Burr development

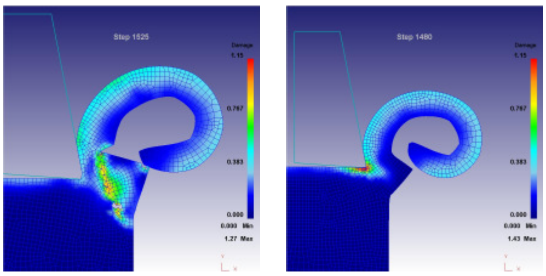

Figure 15 - Phase 5 of the burr formation.

During the burr development in both cases the deformation in the burr shear zone arises.

In case of the treated workpiece the deformation is more located along the boarder between hard and soft material.

Phase 6 – Crack initiation

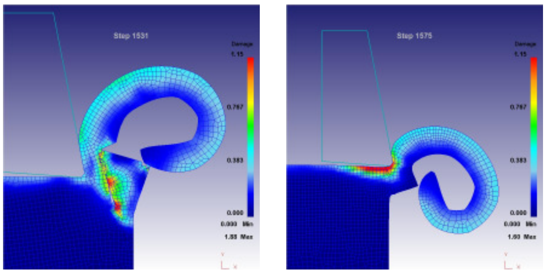

Figure 16 - Phase 6 of the burr formation.

In the case of the hardened workpiece edge the deformations along the replaced burr shear zone reach the critical value for the material deformation. Following, a crack initiates along the deformation plane.
The crack in the case of the untreated workpiece goes along the tool path.

Phase 7 – Crack growth

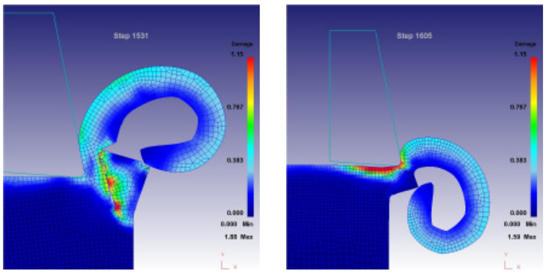

Figure 17 - Phase 7 of the burr formation.

The crack grows in both cases but with different speeds. For the hardened workpiece the crack grows much faster. This is typical for a brittle fracture in comparison to a fracture in ductile material. With this cognition a context between the REM pictures of the fracture surface in the experiments and the fracture speed in the simulation exist.

Phase 8 – Negative and positive burr

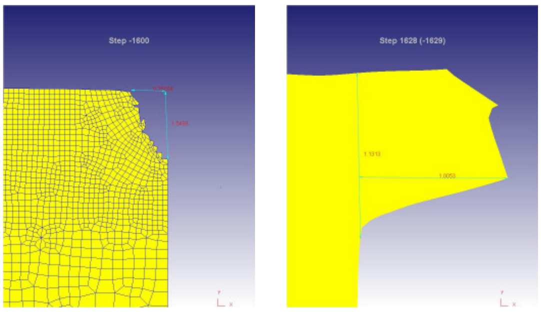

Figure 18 - Phase 8 of the burr formation.

A negative burr is the output of the burr formation on the hardened workpiece edge. In Table 1 the geometries of the negative burr in the experiment is compared with the negative burr in the simulation.

	Burr width	Burr height	Angle	Burr value
	[µm]	[µm]	[°]	[µm]
Exp.	-210	-109	67	-389
Sim.	-1549	-780	64	-1744
Si./Ex.	4.47	4.59		4.48

Table 1: Comparison of the geometries Sim./Exp.

The geometries of the burr in the simulation are much higher than in the experiment. However, there is a scale factor around 4.5 for all geometries and the angle is in the simulation as well as in the experiment, almost the same. Inferential of this cognition, the hardened area in the simulation was modeled too big.
The similar occurrence of the burr in the experiment and in the simulation together with the comparison between the fracture speed and the brittle fracture surface shows that the simulation was close to reality.

3.3 Cutting Forces

One of the most interesting quantitative values of the cutting process is the cutting force. Mostly, the analysis of it shows the load on the tool. In this case the course of the cutting speed over the traverse paths helps to understand the mechanism during the burr formation.

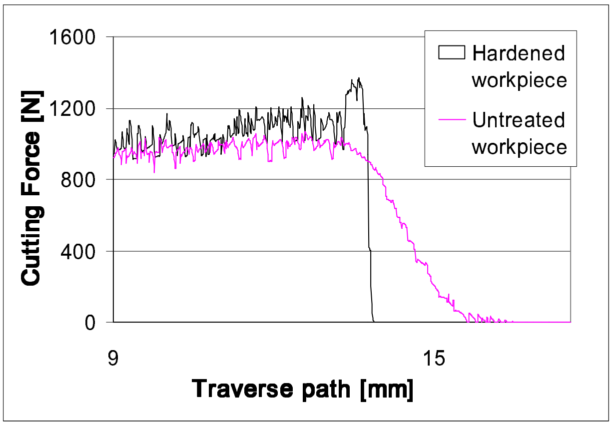

Figure 19: Cutting Forces.

The phases of the burr formation are reflected in the cutting forces. For the untreated workpiece the cutting force is on the beginning on a constant value. When the tool comes close to the workpiece edge and the burr formation begins, the cutting force decreases. The workpiece ends at 15mm, but there is a value over zero for the cutting force for the untreated one. This effect is based on the material which hangs over the edge, which is the so called burr. In case of the hardened material the cutting force goes to zero before the workpiece ends.

This is based on the breaking off of the hardened workpiece edge, confer to phase 7 in chapter 2.6. The course of the graph for the treated workpiece is very different in comparison to the untreated one. In contrast to the constant value for the cutting force of the untreated workpiece the cutting force of the hardened one arises with the beginning of the burr formation. This is based on the higher strength of the hardened material. The force gets to a top value of 1370N and then it drops to zero in 0.25mm traverse path. The fast drop is a sign for a fast-growing crack. When a crack grows fast this is a sign for a brittle fracture. This is, together with the crystalline surface of the negative burr and the fast fracture speed in the burr formation, the third indicator for the theory that the hardening with reduction of the ductility is the cause for a burr free cutting.

4. CONCLUSION

The burr is a quality problem of the modern manufacturing. With the geometry variations of the workpiece edge and the indefinite strength of the burr, it is an imprecision of the component part. Reducing or better avoiding the burr is a goal of many researches. In this paper a new way for reducing and avoiding the burr is shown. It is shown that it is possible to reduce the bur with the hardening of the workpiece edge. In the case of inductive hardening it is possible to avoid the burr and get a negative burr. The negative burr is in its shape close to a trimmed workpiece edge.

The mechanism of the formation of this burr is based on a replacing of the burr shear zone in the zone of the border between hardened and untreated material and a following crack along this replaced burr shear zone. This crack has the character of a brittle fracture, which clarifies that the burr avoiding is based on a reducing of the ductility. Three different aspects can act as verifications. The crystalline surface of the fracture surface, the fast fracture speed and the course of the cutting force with an abrupt fall down to zero are direct evidences for a brittle fracture.

5. ACKNOWLEDGEMENT

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