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Springback in metal cutting with high cutting speeds

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Abstract

In metal forming springback is a widely researched topic. It is generally referred to as the change of part shape that occurs upon removal of constraints after forming. In cutting this also occurs but on a much smaller level. Literature [1-3] shows divers results for mostly static or quasi-static experiments leading to simulations without velocity influence. Experiments done at IWF of ETH Zürich provide results with cutting speeds from v_c =10 to 450 m/min for Aluminium and Titanium. A cutting speed dependency is shown. Capacitive sensors mounted on a custom made tool holder while oblique cutting on a lathe provide online measurements. Experiments include different cutting edge radii, materials and cutting speeds demonstrating the influence of the springback on cutting forces, tool wear and surface roughness.

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Keywords: cutting edge; velocity; springback;

1. Introduction

In metal forming springback is referred to as the change in shape of the workpiece after removing the tool. In metal cutting the same is happening, but on a microscopic scale respectively. While the springback in forming is a prominent issue which was looked at by many researchers, this phenomenon in cutting is often neglected. This paper shows the influence of the springback on cutting forces, flank wear and surface roughness.

Albrecht [1] developed a model for ploughing forces for not ideally sharp cutting edges. He assumed a point of material separation on the rounded cutting edge. Waldorf [2] continued this work. Fig. 1 shows the geometric relationship of material separation point S, where the material either joins the chip or the workpiece. Also demonstrated is the uncut chip thickness t_u, the shear angle Φ and the locating angle α_S. This angle ranges in literature between 60° [4] and 76° [5]. Also the behaviour behind the cutting edge with the different scenarios of material is distinguished between full elastic recovery (iii), plastic recovery (ii) and plastically strained (i) behaviour as can be seen in Fig. 1. The height of the ploughed material δ depending on the cutting edge radius r_n hence is

$$\delta = r_n(1 - \sin\alpha_s) \quad (1)$$

Waldorf [2] gives a good overview of literature attesting each state. Often these experimental studies use static or quasi-static devices with cutting speeds up to 0.75 m/min and rather soft materials like Zinc or Bronze.

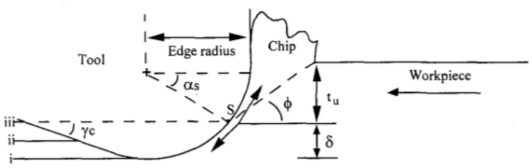

Fig. 1. Cutting with material separation point on edge with 3 recover scenarios [2].

In forming the effect of velocity on the springback was shown by Neugebauer et al. [6]. Velocity effects in the – elastic- plastic behaviour are also visible in stress-strain curves with different strain rates [7]. Cutting simulations, often FEM Models, are done with high cutting speeds due to extreme computation times with lower velocities, therefore validation results are not available. Regarding materials the choice in literature is limited especially because Titanium, known for causing springback issues, was not investigated.

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Titanium has a low Young's modulus compared to steel in the typical range of 100 to 130 GPa. This leads to elastic deformation and to springback after cutting with rounded cutting edges recommended for Titanium cutting [8]. The elastic deformed material behind the cutting edge rubs against the tool's flank face and reduces the effective clearance angle. Also surface quality of the workpiece may be poor. With higher cutting speed and thus higher cutting temperatures the Young's modulus is further decreased increasing the elastic behaviour and therefore the springback. Ezugwu confirms that flank wear is the dominant wear in Titanium cutting just before chipping arises [9]. Fig. 2 exhibits the elastic springback in Titanium cutting causing high compressive stresses on the flank face [8].

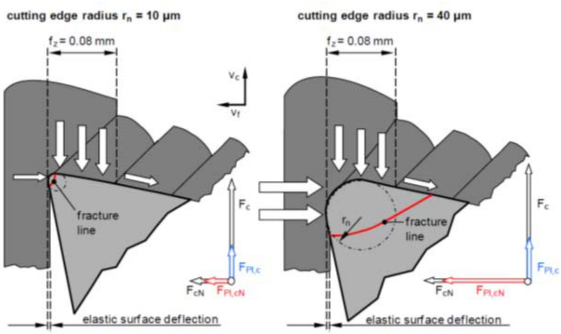

Fig. 2. Tool load on the cutting edge with elastic surface deflection with cutting edge radius r_n (a) 10µm; (b) 40µm [8].

Klocke et al. [10] show that while the cutting speed rises, the cutting forces are going down and the surface quality increases.

Literature shows the dependency of the cutting velocity on the springback and the need for reliable results for various materials, which this paper provides for.

2. Experimental Setup

Longitudinal turning experiments are done on a lathe with a sharp, a blunt tool and a wiper geometry with Aluminium and Titanium and a variation of cutting speed between 10 and 450 m/min. The springback is measured with two different methods. Cutting forces, wear and surface roughness are also recorded.

2.1. Inserts:

Carbide inserts with different micro and macro geometries are used. To identify the influence of the cutting edge radius on the springback a blunt tool with r_n = 72 µm and a sharp tool with r_n = 12 µm are selected. The edge radius is measured on an Alicona Infinite Focus and analyzed using a robust circle fitting method according to Wyen [8]. Both geometries are further described in Table 1. The third insert, a wiper geometry with a wiper parallel to the feed direction and a length of 0.6 mm, is chosen to isolate the springback from the roughness. The wiper geometry used generates a theoretical roughness of zero while cutting with a feed smaller than the wiper length.

Table 1. Tool geometries

Cutting inserts	Corner radius R mm	Clearance angle α deg	Rake angle γ deg	Edge radius r_n µm
Blunt tool	0.8	7	13	72
Sharp tool	0.2	7	23	12
Wiper geometry	0.4	7	18	15

2.2. Workpiece material

The workpiece materials chosen are the Aluminium alloy AlMg1SiSn (Al6262A) and the Titanium alloy Ti6Al4V. Both workpieces have diameters of 100 mm to offer a quasi - flat surface. Both materials feature low Young's modulus and thus high formability. Titanium is predestined to have a high elastic springback due to the low thermal conductivity and hence declining Young's modulus due to a rise in temperature.

2.3. Cutting parameters

The used cutting parameters are shown in Table 2. The cutting depth for all tests is fixed as 0.05 mm, where a thin continuous chip is accomplished. All tests are conducted without cooling fluid. While the feed is chosen as f = 0.1 mm/rev for the standard geometry, the feed for the wiper geometry is three times higher (f = 0.3 mm/rev). Cutting speeds selected for Aluminium range between 10 and 450 m/min and for Titanium 10 – 100 m/min.

Table 2. Used cutting parameters

Depth of cut	a_p	0.05	mm
Feed	f	0.1 (0.3 for wiper)	mm/rev
Cutting speed	v_c	10 – 450 (100 for Ti)	m/min

2.4. Measuring equipment and set-up

Fig. 3 and 4 show the principal measuring set-up and a CAD model. The springback is measured with contactless capacitive sensors from Lion Precision Type C-7 C. With a measuring range of 250 µm, a resolution better than 10 nm and a bandwidth of 15 kHz they offer a good measuring range. In addition a compensation of the curved workpiece surface is done. Process forces are measured with a Kistler dynamometer type 9121. A Talysurf PGI 1240 identifies the roughness values.

The springback measuring consists of three contactless capacitive sensors as displayed in Fig. 3. Sensor 1 and 2 are fixed on the machine and thus not moving. While Sensor 1 is just measuring the workpiece deflection due to process forces, Sensor 2 is measuring the workpiece distance before and after the tool has passed. Hence Sensor 2 is measuring the depth of cut a_p (here: X) minus the springback δ. Sensor 3 is fixed on the tool holder with a set distance between the cutting edge and the sensor. Once this distance is calibrated, the springback δ can be calculated as the deviation.

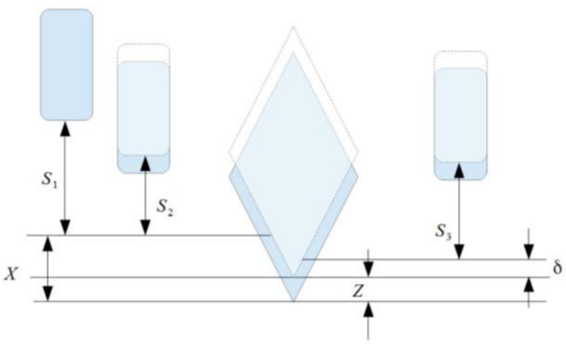

Fig. 3. Principle measuring set-up including Sensors 1-3 and cutting insert

Value Z in Fig. 3 marks the measuring uncertainty, which occurs due to various reasons:

- Tool displacement due to temperature
- Tool displacement due to process forces
- Repeatability / precision of the lathe
- Roughness difference before and after the cut

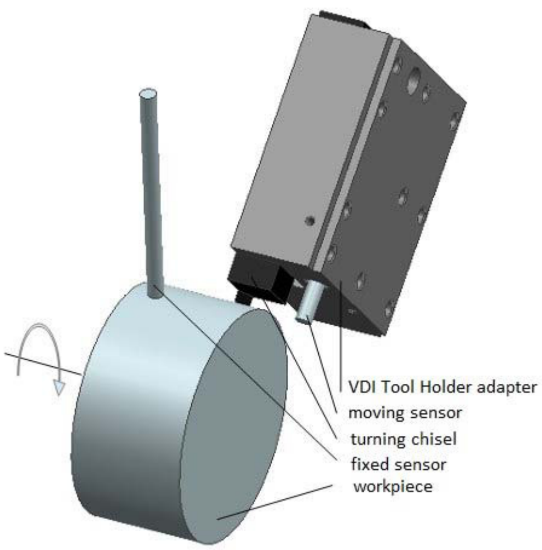

Fig. 4. Model of measuring set-up.

2.5. Measuring error

Fig. 5 shows the Ishikawa diagram leading to the measuring error. Main causes to the error are measure uncertainty, temperature, work piece roughness and cutting forces. In the measure uncertainty the repeatability and accuracy of the machine tool and of the sensors have to be taken into account while the design is responsible for a stable set-up of tool, work piece and sensors. In temperature considerations the thermal expansion of the set-up can be reduced to the insert because of the design and the sensor being installed on the tool holder. The work piece roughness can also be neglected when cutting with the same parameters as the previous cut, thus the sensors were calibrated on the same roughness. Problems are arising when a built up edge is cutting instead of the cutting edge. The cutting depth is higher and undefined and thus the springback cannot be calculated. The cutting speed sector, where built up edge is occurring has to be skipped. In regards to the cutting force the compliance of the set-up has to be taken into account. Due to the design of sensor and tool on one holder the error of measurement can be kept at a minimum. The indicated measuring errors are identified with additional experiments including positioning, temperature and compliance measuring resulting in:

- Error due to repeatability: 0.35 µm
- Error due to temperature: 0.59 µm ($\Delta T_{max} = 17°$ K)
- Error due to cutting forces: 0.51 µm ($\Delta F_{max} = 70$ N)

With these influences an uncertainty range u can be defined with:

$$u = \sqrt{\sum u_i^2} = \pm 0.851\ \mu m \qquad (2)$$

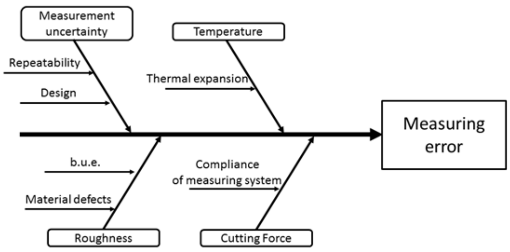

Fig. 5. Ishikawa diagram of the measuring error in springback measurements.

3. Results

Fig. 6 shows an overview of the springback of Aluminium AlMgSi1Sn and Titanium Ti6Al4V with a blunt and a sharp tool including error bars. According to literature data the maximum springback would range as shown in Table 3.

Table 3. Literature values for maximum springback

Blunt tool	$r_n = 72$ µm	δ = 2.1 – 9.6 µm
Sharp tool	$r_n = 12$ µm	δ = 0.3 – 1.6 µm

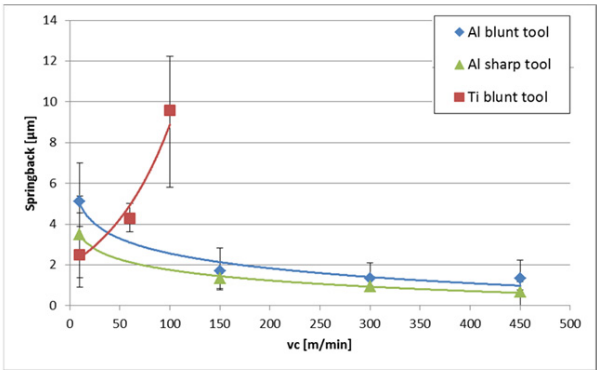

Fig. 6. Overview of the springback with sharp and blunt tool in Aluminium and Titanium machining.

The influence of the cutting speed on the springback is significant. For Aluminium the springback is declining with rising cutting speed reaching a steady state with higher cutting speeds (v_c > 200 m/min). This shows the existence of the material separation point and points out elastic behaviour with low strain rates, changing to plastic deformation with higher velocities. Titanium is behaving differently and the springback is rising with the velocity. This is due to the low thermal conductivity, hence the further lowered Young's modulus as well as the higher yield strength and thus less plastic deformation. With room temperature the Young's modulus of Titanium is about 1.5 times higher than of Aluminium. The yield strength in room temperature of Ti6Al4V is about 3.5 higher than of AlMgSi1Sn. Looking at Fig. 6 and low cutting speeds of v_c = 10 m/min we can see a higher springback in Aluminium than Titanium. With rising cutting speed this changes with a rising springback in Ti and a declining in Al. Also visible is the influence of the cutting edge radius. The springback for the sharp tool is always lower than for the blunt tool. Comparing the measurements in Fig. 6 with the literature [2] values in table 3 a good agreement with the blunt tool and low cutting speeds can be found. For higher cutting speeds and the sharp tool this cannot be attested. An overestimation of the cutting edge radius and an underestimation of the cutting speed are demonstrated.

3.1. Surface Quality

In Fig. 7 the influence of the surface quality in feed direction compared to the springback is shown. To emphasize this, a wiper geometry combined with a higher feed of f = 0.3 mm/rev is utilised. Because the wiper length is bigger than the feed, the geometric roughness is zero. Thus the roughness shows the influence of the springback directly only showing an error of form because of production accuracy. Special about the wiper is also that the wiper is cutting two times over a point due to the wiper length of 0.6 mm. This interacts with the springback and the roughness respectively. Nevertheless one can see a high coherence of R_a and the springback. Also visible is a velocity dependency. The higher springback respectively the roughness with higher cutting speeds is due to the multiple passages of the tool where material is ripped out instead of flattened.

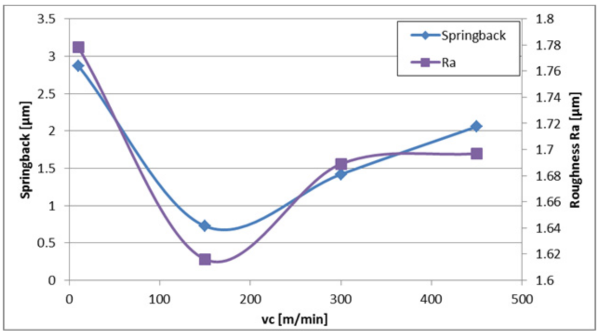

Fig. 7. Influence of the springback on the surface roughness R_a when cutting with wiper geometry AlMg1SiSn, f = 0.3 mm/rev, a_p = 0.05 mm

3.2. Tool Wear

Fig. 8 shows the flank wear for the blunt tool after cutting Titanium with v_c = 10 m/min (left) and v_c = 100 m/min (right) and a cutting length of 0.2 m. Fig. 9 points out this relation to the springback. While the springback rises the flank wear also increases pointing out the theory of various researchers [8, 9].

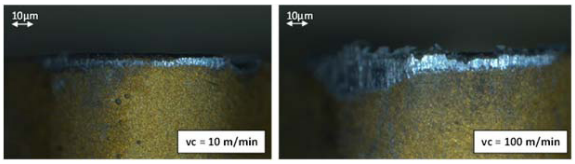

Fig. 8. Tool flank wear after cutting Titanium with (a) vc = 10 m/min; (b) vc = 100 m/min and 0.2 m cutting length.

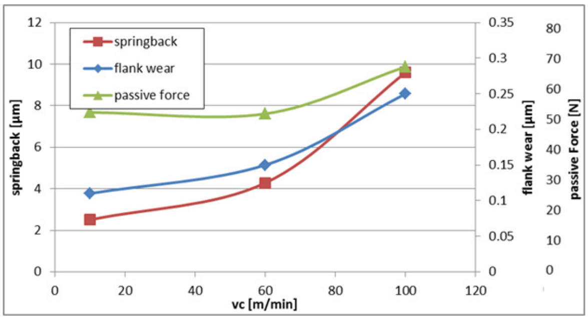

Fig. 9. Influence of the springback on the flank wear and the passive forces when cutting Ti6Al4V.

3.3. Process Forces

Fig. 9 connects passive force, representing the most influenced process force, with the springback in cutting titanium with blunt tools. A similar curve progression is displayed as in flank wear. The passive force increases from 52 N to 75 N with increasing cutting speed and increasing springback. Reasons are the same as in flank wear and demonstrate the importance of the springback.

4. Conclusion and Outlook

Springback in cutting with rounded cutting edges is presented and its effect on surface quality, tool wear and process forces is displayed. A measuring method in longitudinal turning is described providing reliable data in relation to the cutting speed. Besides confirming literature data for certain conditions a velocity dependency is provided. Springback behind the cutting edge in Aluminium declines with increasing cutting speed while in Titanium machining it increases. This effect is shown in further comparison to the surface roughness, tool flank wear and process forces. This data can help to improve simulation results of cutting processes and to understand the importance of elastic-plastic effects of materials. Furthermore this can help to find cutting conditions for Titanium cutting where flank wear and high passive forces can be reduced to a minimum.

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