CZASOPISMO TECHNICZNE M
WYDAWNICTWO POLITECHNIKI KRAKOWSKIEJ

z. 9-M/2008
ISSN 0011-4561
ISSN 1897-6328

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VERIFICATION OF MACHINABILITY OF AUSTENITIC STAINLESS STEELS DURING TURNING

WERYFIKACJA SKRAWALNOŚCI NIERDZEWNYCH STALI AUSTENITYCZNYCH PODCZAS TOCZENIA

A b s t r a c t

This article presents results of machinability tests on austenitic stainless steels and describes appropriate parameters for the cutting zone during the process of turning. The article focuses on the analysis of selected domains through four basic indicators of steel machinability: kinematic, dynamic, surface quality, production, and shaping, with the goal of proposing recommendations for austenitic stainless steels, and to integrate current knowledge in this field with turning theory and practice.

Keywords: *cutting, cutting zone, plastic deformation, stainless steels, cutting tool, turning, machinability*

S t r e s z c z e n i e

W niniejszym artykule zaprezentowano wyniki testów skrawalności nierdzewnych stali austenitycznych i opisano odpowiednie parametry dla strefy skrawania w procesie toczenia. Przedstawiono analizę wybranych obszarów poprzez cztery podstawowe wskaźniki skrawalności stali: kinematyczny, dynamiczny, jakości powierzchni, produkcji i strugania poprzecznego (formowania). Celem analizy jest zaproponowanie nierdzewnych stali austenitycznych oraz zintegrowanie obecnej wiedzy w tej dziedzinie z teorią toczenia i praktyką.

Słowa kluczowe: *strefa skrawania, odkształcenie plastyczne, stale nierdzewne, nóż, toczenie, skrawalność*

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1. Introduction

Automated production in the sense of machine production has characteristic features: a reduction of production costs, stimulation of the development of cutting tools, and changes in the construction of machine tools, all of which work against the creation of optimal technological methods, which thrusts the technological process of cutting into a more important position. These trends confirm that the cutting process remains one of the basic manufacturing technologies. A condition of the economic usage of modern, automated programmed turning machines is the optimal course of the cutting process, i.e. the use of optimal work conditions. A summary of optimal work conditions requires knowledge of the laws of cutting theory and knowledge of the practical conditions of their application.

This article presents the results of experiments that concerned the verification of machinability of work pieces of difference types of 18/8 austenitic stainless steel (steel 1.4301 according to DIN nomenclature).

2. Austenitic Stainless Steels

Stainless steels are fundamentally subdivided by their chemical composition and metallographic structure.

The individual elements occur in different ratios, as shown in Table 1. The heading chromium includes the elements chrome, molybdenum, silicon, niobium, aluminium, vanadium, titanium, tantalum, and tungsten. The elements nickel, carbon, manganese, copper, and nitrogen are included under the heading of nickel. Stainless steels can contain elements in addition to the above as well: maxima of 0.040% of phosphorus, 0.035% of sulphur, 0.90% of manganese and 0.70% silicon.

T a b l e 1

Ratio of chemical elements determined through analysis of chrome equivalent according to various authors [1]

Author	Chemical Element								
	Ni	Mn	C	N	Cr	Mo	Si	Nb	Ti
Schaeffler	1	0,5	30	–	1	1	1,5	0,5	–
De Long	1	0,5	30	30	1	1	1,5	0,5	–
Juferov	1	0,1	20	–	1	1	1,5	0,5	4
Adrew	1	0,5	21	11,5	1	1	3,0	4	10
Fleischmann	1	0,5	30	–	1	2	–	–	–
Post-Eberly	1	0,5	35	–	1	1,5	–	–	–
Fišman	1	0,35	28	–	1	–	2	–	3,1
Myerhofer	1	0,8	24	–	1	0,9	–	2	–
Newell	1	0,5	30	–	1	2	–	–	–

3. Evaluation and Experimental Parts

This article concerns itself with the evaluation of selected domains of machinability in compliance with EN ISO 3685 [2] standards. The experiments were performed in laboratory conditions and verified in real conditions during manufacture. The set-up used (Fig. 1) contained the following components: a SUI 40 turning machine with gas regulation of rotational frequency, a WNMG 08408-NF cutting tool with M20 cutter, and PWLNR 2020 K-08 tool holder. The materials to be machined were three types of austenitic stainless steels with chemical composition listed in Table 2. The diameter of each piece was of (*d*) of 100 mm and length (*l*) of 300 mm. The cutting process employed was axial dry machining (DM), and the cutting frequency was defined at intervals of v_c = 50 to 300 m/min, the feed was advanced from intervals of f = 0.023 to 1.125 millimetres, and cutting depth a_P = 1.0 mm.

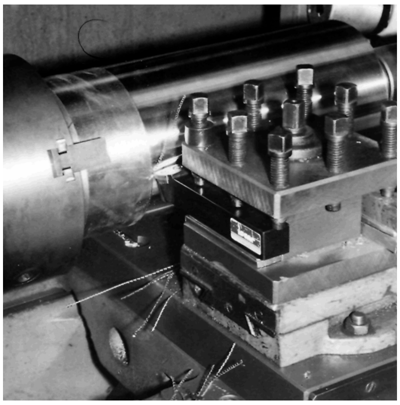

Fig. 1. Turning System
Rys. 1. System toczący

T a b l e 2

Chemical composition of austenitic stainless steels

Type of Steel	Chemical Composition wt [%]							
	C	Cr	Ni	Mn	Ti	Si	P	S
1.4301	0.07	20.0	10.0	2.0	–	1.0	0.045	0.030
1.4571	0.08	18.0	9.0	2.0	0.4	1.0	0.045	0.030
1.4571	0.08	17.0	12.0	1.8	–	1.0	0.045	0.030

Researching the cutting zone (the interaction between the tool, the workpiece, and the cuttings) is to capture its state at the moment of the creation of the cutting (the so-called root of the chip), shown in Fig. 2. Cutting zone testing and analysis under a microscope (Fig. 2) shows that different regions of smoothly-formed chips can be described.

The process of cutting is the mutual interaction between the tool and the workpiece, which is controlled by many phenomena, which creates a synergistic effect. An understanding of the phenomena and domains involved arises from cutting zone experiments [4]. Figure 3 is a model of the cutting zone, which illustrates the underlying phenomena in the separation of the cutting from the material of the workpiece. It is important to define the shear level in the cutting zone.

Weber [5] states, that the depth of the shear level follows the formula $0.05\ h \leq h_{SP} \leq$ $\leq 0.1\ h$, where h is the thickness of the cut section and h_{SP} is the depth of the shear level. The size of this local region was determined through the help of electron microscope analysis, and the results are displayed in Table 3. We observe elements from the cut layer

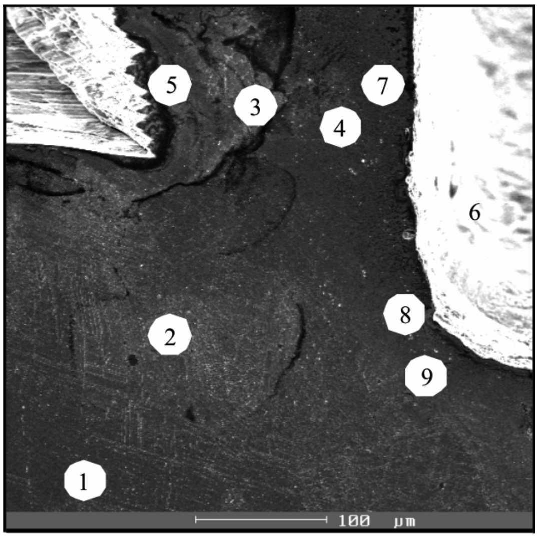

Fig. 2. Tested cutting zone [3]: 1 – non-deformed material structure, 2 – plastic deformation zone with defined width (shear volume), 3 – central part of the chip, displaying a high level of strain hardening, 4 – region of the cutting deformed by the action of friction, 5 – the loose central part of the cutting, irregular in shape, 6 – the cutting surface of the tool, (7 – the contact region between chip and cutting tool face, 8 – built up edge on the cutting tool edge, 9 – the contact region between the machined surface and cutting tool flank)

Rys. 2. Testowana strefa skrawania [3]: 1 – struktura nieodkształconego materiału, 2 – strefa plastycznej deformacji ze zdefiniowaną szerokością (objętość ścinania), 3 – centralna część wióra ukazująca wysoki stopień umocnienia zgniotowego, 4 – obszar ścinania zdeformowany przez działanie tarcia, 5 – luźna centralna część skrawania, nieregularna w kształcie, 6 – powierzchnia tnąca narzędzia, (7 – obszar stykania się wióra z czołem, 8 – krawędź narastania na krawędzi noża, 9 – obszar stykania się obrabianej powierzchni i powierzchni bocznej noża)

in the shear layer that have been displayed (they melt the cutting wedge). The thickness of the cut layer continually varies chip thickness h_1. Chip formation is described by Hencky and Zorev [6] through the theory of plasticity. The presence of strain lines in chip formation is depicted in Fig. 4. For steel 1.4301 it is characteristic that the chip texture is variable, and has a general shape as shown in Figure 3. Another distinction is the marked destruction in the area in front of the cutting wedge, as shown in Fig. 4. The cutting process is accompanied by elastic and plastic deformations during chip division and friction between the tool and the workpiece. It is possible to define four separate regions in the cutting zone where these actions play out. The first zone between the chip and the workpiece, called the shear layer, divides the non-deformed region from the deformed chip under the angle

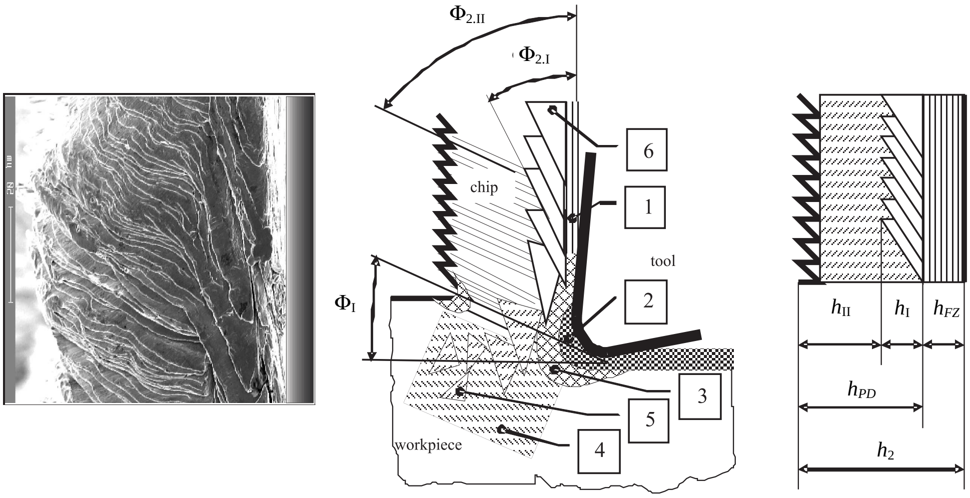

Fig. 3. Cutting zone and model of chip formation during turning of steel 1.4301: 1 – Flow Zone, 2 – stress hardening of the surface at the point of cutting, 3 – volume of driven material, 4 – shear plane, 5 – beginning of creation of solid segments of material, 6 – chip fragments, (Φ_I – angle of the shear level, $\Phi_{2.I}$ – first-zone chip angle, $\Phi_{2.II}$ – second-zone chip angle)

Rys. 3. Strefa skrawania i model formowania wióra podczas toczenia stali 1.4301: 1 – strefa przepływu (płynięcia), 2 – utwardzanie powierzchni w punkcie skrawania, 3 – objętość materiału wciskanego, 4 – powierzchnia ścinania, 5 – początek formowania litych segmentów materiału, 6 – fragmenty wióra (Φ_I – kąt poziomu ścinania, $\Phi_{2.I}$ – kąt pierwszej strefy wióra, $\Phi_{2.II}$ – kąt drugiej strefy wióra)

of the shear layer (indicated by Φ_1), which is defined as identical to the boundary angle of deformation. The second zone is the area where cracks arise and widen. Cracks arise as a result of the between the strength of the material on the cut level and are caused by the dividing of the material in the form of chips. A chip arises along the entire surface of the tool, and the third zone is the zone of intensive friction between the chip and the tool. The engaged cutting wedge is subject to intensive stress not only in the face plate, but also on the side plate in the fourth zone.

The results of cutting zone evaluation (Fig. 4) under cutting conditions (v_c = 100 m/min, a_P = 1 mm and f = 0.210 mm) are a definition of shear level angle and the texture angle. For 1.4301 steel Φ_I is 31 to 33°, for 1.4541 steel Φ_I is 35 to 36°, and for 1.4571 steel Φ_I is 37 to 38°. For 1.4301 steel $\Phi_{2.I}$ is 20 to 22° and $\Phi_{2.II}$ is 42 to 45°, and for 1.4571 steel $\Phi_{2.I}$ is 25 to 27° and $\Phi_{2.II}$ is 44 to 45°. Also important are the values of the depth of the plastically-deformed material (of the chip), the flow zone and the strain hardness of the machined surface. For the defined experimental conditions, (v_c = 100 m/min, a_P = 1 mm and f = 0.210 mm), the values stated in Table 3 were achieved.

Table 3

Cutting Zone Parameters

Steel	h_t [mm]			h_h [mm]	h_{SP} [mm]
	h_I [mm]	h_{II} [mm]	h_{FZ} [mm]		
1.4301	(16–18 %) h_t	(70–75 %) h_t	(7–14 %) h_t	0,4	0,1–0,2
1.4541	(18–22 %) h_t	(68–70 %) h_t	(8–14 %) h_t	0,5	0,1–0,15
1.4571	(22–26 %) h_t	(65–68 %) h_t	(6–13 %) h_t	0,6	0,08–0,12

Where h_1 is the cutting width, $h_1 = h_{PD} + h_{FZ}$, h_I is the depth of the I. Zone, h_{II} is the depth of the II. Zone, h_{FZ} is the depth of the flow zone, h_{PD} is the depth of the plastically-deformed material, $h_{PD} = h_I + h_{II}$, h_h is the depth of the hardened machined surface and h_{SP} is the depth of the shear layer.

a) b) c) d) e) f)

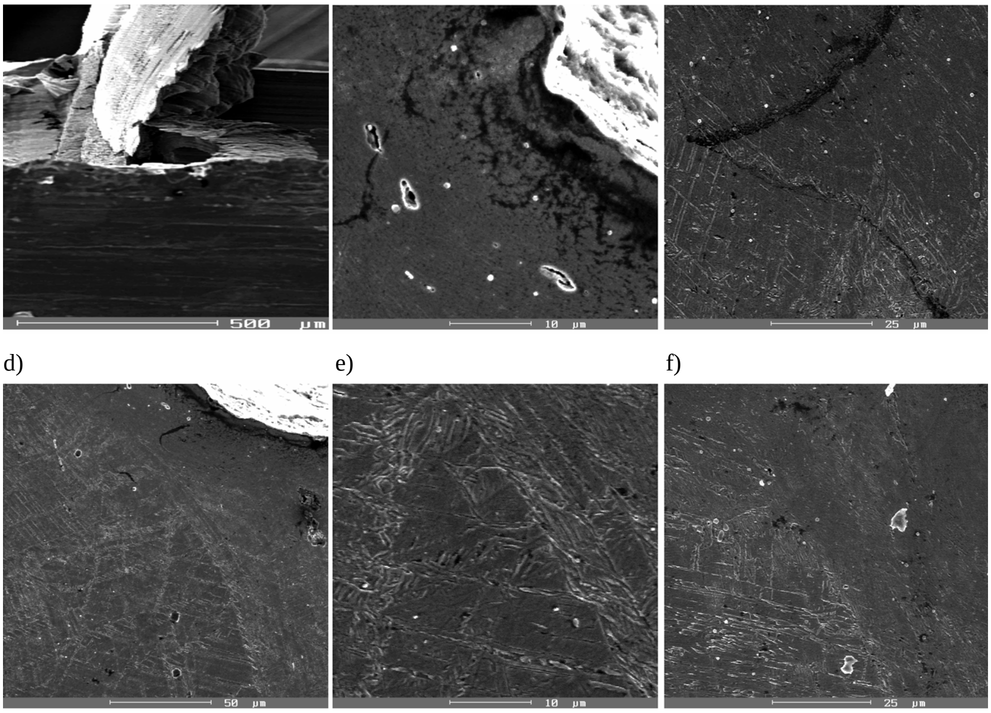

Fig. 4. Cutting zone for austenitic stainless steel 1.4301: a) chip root, b) material destruction in front of cutting wedge, c) primary zone of plastic deformation, d) plastic deformation-slippage field, e) slip lines, f) boundary between the deformed and non-deformed material

Rys. 4. Strefa skrawania dla nierdzewnej stali austenitycznej 1.4301: a) rdzeń wióra, b) zniszczenie materiału z przodu klina tnącego, c) główna strefa odkształcenia plastycznego, d) pole plastycznego poślizgu odkształcenia, e) linie poślizgu, f) granica pomiędzy odkształconym i nieodkształconym materiałem

4. Workpiece Machinability

In the course of material selection, the cutting process generally can arise from the traits which the workpiece and the conditions of the cutting process. This character is material machinability. According to Cook [7] machinability is a quality of the material that expresses its capacity to machine the work piece from the point of view of its functional qualities. Creation and formation of chips and tool wear of the cutting edge of the cutting edge of influence the capacity of workpiece processing.

The wear criterium VB_k = 0.3 mm was applied during evaluation. The cutting process conditions were designed based on the needs of the material and on the operation of the finished surface. The results of the long-term test after exhaustive analysis of selected data are shows on Fig. 5.

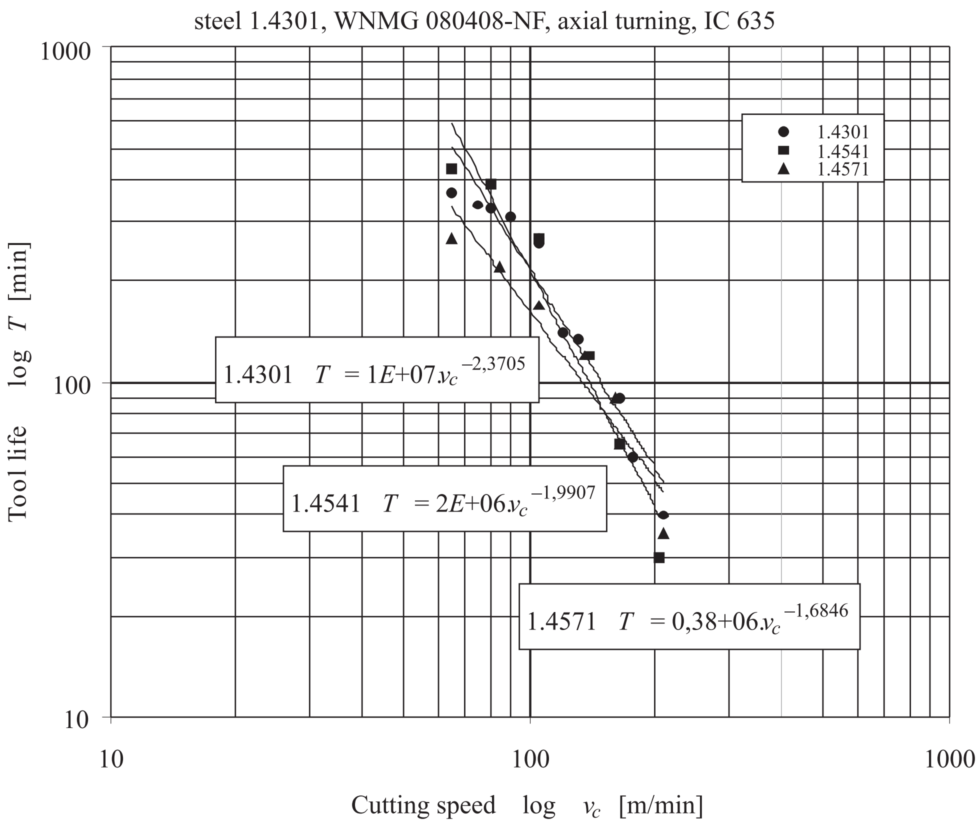

Fig. 5. Relation between the tool life log T and cutting speed log v_c
Rys. 5. Zależność pomiędzy trwałością narzędzia (noża) log T i prędkością skrawania log v_c

The relation in Figure 5 is also shown with correlating coefficients, by which the results are significant and result in a functional relation ($R > 0.9$). In Table 4, the Taylor tool life equations for individual types of stainless steels are shown. Parameter m for sintered carbides has a value following Table 4. For comparison, a planned experiment method was also applied with the task of verifying the accuracy of measured results and recommendation of this method for other applications. The results of this method are documented in Table 4, where the vales shown are appropriately acquired values from analysis of measured values (Fig. 5).

Damage to the cutting edge of the tool in conditions greater than (v_c = 180 m/min, a_P = 1 mm and f = 0.8 mm) is characterized on Fig. 6.

Table 4

Tool life equations based on results of measurements

Steel	Taylor equation [experimental]	Taylor equation [measurement]
1.4301	$T = \frac{1055{,}22 \cdot 10^4}{v_c^{2,3652}}$	$T = \frac{1000{,}24 \cdot 10^4}{v_c^{2,3705}}$
1.4541	$T = \frac{1995{,}44 \cdot 10^3}{v_c^{2,06}}$	$T = \frac{2000{,}17 \cdot 10^3}{v_c^{1,9907}}$
1.4571	$T = \frac{395{,}52 \cdot 10^3}{v_c^{1,7061}}$	$T = \frac{380{,}78 \cdot 10^3}{v_c^{1,6846}}$

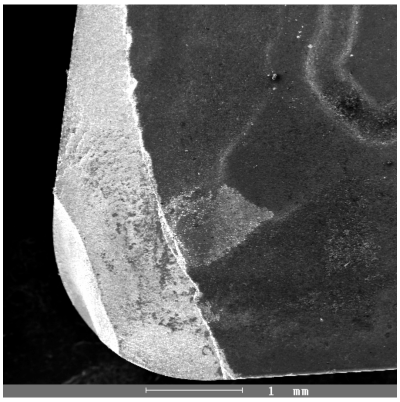

Fig. 6. Face plate damage to cutting edge
Rys. 6. Uszkodzenie tarczy tokarskiej krawędzi noża

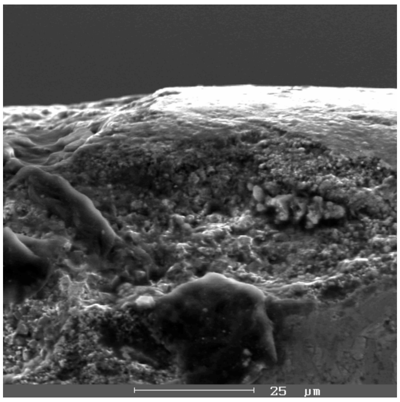

Fig. 7. Cutting tool face plate wear-formation of channels on the main cutting
Rys. 7. Formowanie kanałów ścierania tarczy tokarskiej noża w głównym skrawaniu

As has already been shown, machining of austenitic stainless steels involves very low thermal conductivity, which dissipates heat very slowly from the cutting zone. This often contributes to the channel formation on the face plate. Figure 7 even shows melted work piece material on the surface of the cutting tool.

5. Cutting force components on the tool cutting edge

Cutting force F acts on the cross-section of the cut layer. Resistance of the cut layer to the main component of cutting force F_C is known as cutting resistance. The action of the main cutting force component F_C is the specific cutting force, according to Kienzl and Victor [8]. The goal of measuring these dynamic constituents is to define the size of these constituents, the magnitude of the specific cutting force and to compare the achieved results, with the aim of recommending solutions for practical use. This analysis was obtained with the aid of a tricomponent piezoelectric dynamometer (KISTLER 9257A). Continually-recorded data was analyzed on a PC and compared to form the graphical dependency in Fig. 8. Figure 8 depicts the dependence of specific cutting force on the feed at different levels of cutting speed. The results are interesting from two standpoints: at smaller values of chip cross-section (feed values up to 0.2 mm) the specific cutting force

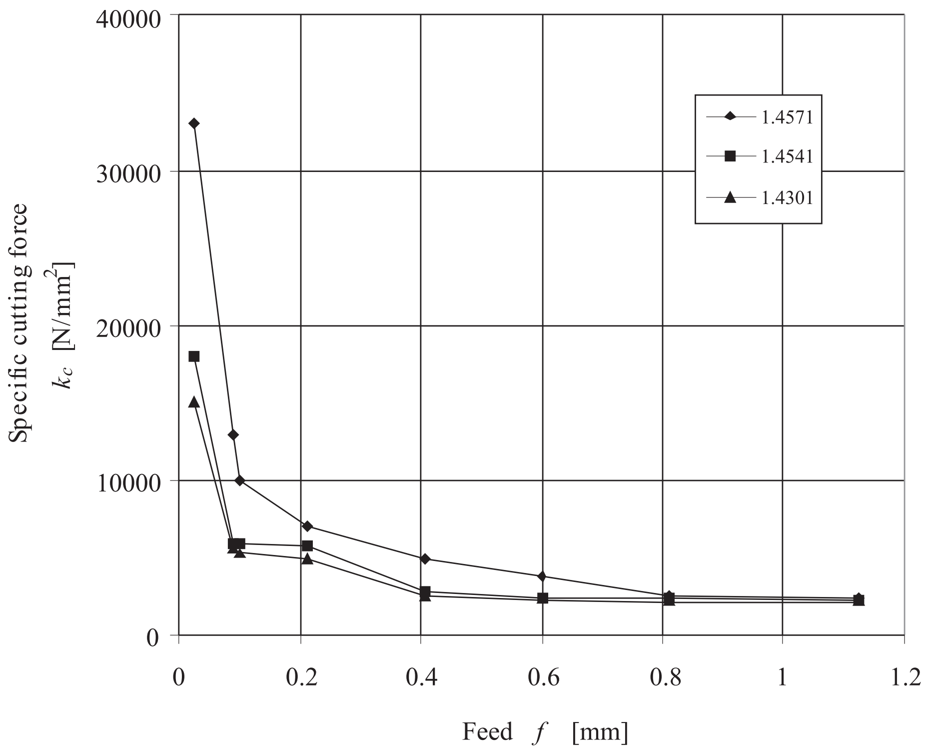

Fig. 8. Dependency of specific cutting force on feed
Rys. 8. Zależność danej siły skrawania od posuwu

was much higher, achieving values up to 33000 MPa. For greater values of chip cross--section (for feed values above 0.2 mm) the value of the specific cutting force peaks at 3000 to 5000 MPa. A second important conclusion is that as the cutting speed approximately doubles (e.g., for 60 m/min to 120 m/min) for small values of chip cross-section (feed values up to 0.2 mm) the specific cutting force is about half as large, reaching values around 17000 MPa. For greater chip cross-sections (feed values above 0.2 mm) the value of the specific cutting force peaks at around 3000 MPa. From this follows the need to define higher cutting speeds.

The region of slip contact has an important role in turning. One of the phenomena that results from the interaction of the workpiece and the cutting portion of the tool is the creation of a hanging layer on the faceplate and side plates of the tool that we call the scab. Makarov [9] describes the gradual stages of scab formation as a periodic phenomenon that quite negatively influences the cutting process. The scab can be stable-that is, is does not change size after reaching a certain point, nor does it take over the function of the cutting edge, simultaneously reducing the intensity of its wear. An unstable scab increases cutting wear. Currently, the scab accounts for one of the forms of the external appearance of the phenomenon of tool cutting edge wear. The scab is one of the important factors which influences a change in the specific cutting force, which is formed with steel 1.4301 mainly at cutting speeds between 50 and 60 m/min. A variable (unstable) scab forms on the side plate, which gradually strips off during the process. For C45 steels this region is defined at cutting speeds of around 25 to 30 m/min. The components of cutting force increase as the radial and tangential components grow faster than the feed component. At cutting speeds of 60 m/min there was a clear jump in these changes, caused by the formation of the scab. According to [10] we can express these components as eq. (1). The final relation during turning according to eq. (1) is stated in Table 5.

$$F_c = A \cdot a_p^a \cdot f^b \tag{1}$$

Table 5

Components of cutting force for stainless steel expressed as a relation to eq. (1)

Steel	Componential equation for cutting force [N]
1.4301	$F_f = 16{,}25.10^6 \cdot a_p^{1,6221} \cdot f^{0,3795},\ F_p = 3706{,}245 \cdot a_p^{1,1121} \cdot f^{0,4217},\ F_c = 2033{,}111 \cdot a_p^{0,9985} \cdot f^{0,4215}$
1.4541	$F_f = 2845{,}222 \cdot a_p^{1,4302} \cdot f^{0,7165},\ F_p = 1983{,}036 \cdot a_p^{0,9532} \cdot f^{0,8225},\ F_c = 1678{,}544 \cdot a_p^{1,1115} \cdot f^{0,3795}$
1.4571	$F_f = 4568{,}998 \cdot a_p^{1,6221} \cdot f^{0,7375},\ F_p = 2745{,}264 \cdot a_p^{1,4551} \cdot f^{0,7864},\ F_c = 2015{,}876 \cdot a_p^{1,3781} \cdot f^{0,8523}$

The microgeometry of the outer surface is characterised by microgeometric chipping. For evaluating the outer surface after turning and defining the cutting process conditions, the following parameters were used in the investigation: the outer surface roughness parameter *Ra* [µm] was measured on two measuring instruments, a HOMEL TESTER T 1000C and a HOMEL TESTER T 6 D, the hardness of the outer surface layer was evaluated following Brinnell [HB] with the help of a hardness tester, the microhardness of the outer surface layer was evaluated following Vickers [HV] with the help of another hardness tester, increased tension and morphology of the outer surface after cutting were evaluated after careful analysis using an X-ray microscope. For the turning itself, following many authors, it is possible to set the range of vales for the *Ra* parameter from 1.6 to

3.2 µm. For other conditions, this value can be placed in intervals from 0.8 to 1.6 µm. The measured results are documented in Table 6.

Table 6

Measures parameter values for outer surface roughness *Ra* v [µm]

		Cutting speed v_c [m/min]					
		50	100	180	200	250	300
Feed f [mm]	0,023	1,31	1,52	1,35	1,43	2,03	2,36
	0,09	1,56	1,46	1,32	1,54	1,99	2,44
	0,102	1,24	0,71	0,65	0,68	1,45	2,55
	0,405	1,58	1,25	0,87	0,75	1,78	2,91
	0,6	2,22	2,34	0,95	0,88	2,47	3,55
	0,8	2,85	2,87	1,05	0,98	3,33	3,87
	1,125	3,52	3,92	1,15	1,02	3,89	4,08

The acquired results are interesting in that for the defined conditions we can achieve a quality outer surface after cutting with roughness parameters down to around 0.7 µm. When turning, it is not an advantage to a feed of lower than 0.09 mm for the roughness criteria of the outer surface. Very good results were mainly achieved when cutting speed was 100 m/min and the feed was 0.102 mm. Similar roughness in the outer surfaces of the individual type is not based on differences in the quality of the outer surface. The value of *Rz* (following ISO 4287, it is the upper limit of unevenness in outer surfaces) did not exceed a value of 6 µm.

Before turning, the hardness of the basic structure of 1.4301 steel was measured at 190 HB (corresponding to a hardness of 194 HV), the hardness of the basic structure of 1.4541 steel was 195 HB (corresponding to 198 HV) and the hardness of the basic structure of 1.4571 steel was 198 HB (corresponding to 202 HV). After turning, outer surface hardness was measured and the results are presented in Image 27. As shown in Image 27, outer layer hardness increased by 20 to 25% for 1.4301 steel, by 25 to 28% for 1.4541 steel and by 25 to 30% for 1.4571 steel. It is very significant that the hardness of the outer surface after cutting increases with an increase in cutting speed and decreases with an increase in feed value.

6. Chip forming

The chip forming in the cutting zone belong among the basic information regarding the investigation of cutting theory and have been dealt with by many authors, for example Ernst and Merchant, Bailey and Boothroyd, Loladze and others. The authors' theories are varied, although no model for the shaping of shavings can be applied to all machined materials. The process of chip forming by turning austenitic stainless steel is very problematic as the material is very tough, and the results of which are documented in intensive plastic deformation inside the chips (chipped lines to chipped fields). Small section shavings (feed f = 0.1 to 0.4 mm, cutting depth a_p = 1.0 mm) are characterized by shaving sections with a section similar to Fig. 9. Larger section chips (feed f = 0.4 to 1.125 mm and cutting depth a_p = 1.0) are characterized by full chips with sections.

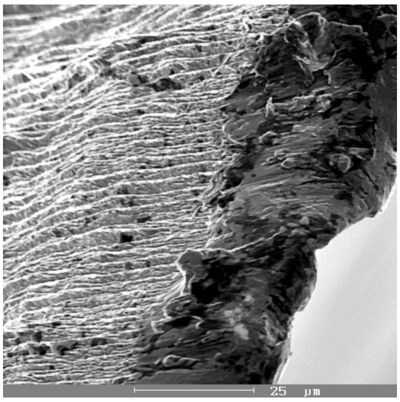

Fig. 9. Plastic deformation in a shaving section, 1.4301 steel
Rys. 9. Odkształcenie plastyczne w sekcji wiórkowania, stal 1.4301

Sections of shavings document very intensive plastic deformation in the shavings themselves. The physical and mechanical characteristics of these steels predetermine their processing. In spite of their excellent qualities, they also have their drawbacks. As a result, all information gained through real interpretation and undertaken research on local hardening can push science in the given field further.

7. Conclusions

It is important for both theory and practical applications that essential conclusions come from measurement and analysis. Results were acquired under laboratory conditions and performed in a tool shop. The conclusions are as follows:

- Defined tool life equation following Taylor.
- Defined the equation for the cutting strength components.
- Designed a model to generate shavings.
- Confirmation of surface strain hardening (change in mechanical properties) after cutting.
- Defined coefficients for kinetic machining of austenitic stainless steels, whereby 1.4301 steel, k_p = 0.52–0.54, for 1.4541 steel, k_p = 0.51–0.53 and for 1.4571 steel, k_p = = 0.49–0.52. For C45 steel, the coefficient of kinetic machining is k_p = 1.0.
- The machinability of austenitic stainless steel is two to three times worse that than for C45 on the basis of its chemical components: mainly chromium, nickel and other component elements.
- Maintain documentation of work piece material documents.
- The basic factor involved with oversized blunt tools is high temperature in the cutting zone. In order to increase the durability of the tools' cutting heads, it is necessary to lower this temperature. This is possible on the one hand by increasing the thermal conductivity of the steel used for production (changes to chemical composition) without lowering its basic elements like sulphur, selenium, bismuth or boron, or by means of a second option that has been used for a long time in practical applications: intensive cooling of the process medium.
- For the cutting process, it is necessary to use a tool that has a large cross section so that it can sufficiently dissipate the heat formed from the cutting zone.

- The wear of cutting tools may also affect the selection of appropriate geometry, mainly the positive angle of the front of the tool as well as the required high surface quality of the tool's effective area.
- Recommend the preferred use of cutting tools with laminated surface sintered carbides when it is necessary to secure high rigidity and machine-tool-jig-work piece system stability.
- Complete work with sharp tools, change tools immediately upon minor wear or damage.
- It is better to work with a highly durable tool with regard its maximum attained cutting speed.
- Avoid cutting interval speeds of 50 to 60 m/min, large feeds, lowered hardness in the cutting zones and low cutting speeds.
- Develop new forms of cutting techniques for materials.
- Use vibration in the cutting process system to improve the process of removing shavings if allowed by the required outer surface quality after cutting.
- Use new technological procedures (change cutting conditions, mainly feed and turning frequency).
- Ensure the technological discipline of workers (maintenance of conditions contained in technical documentation).

On the basis of experience, the authors recommend, for machining these types of steels, selecting criteria for automated production process based on the following order: For rough machining operations – in first position, forming of shavings, kinematic processes, dynamic processes and outer surface quality after cutting. For finished work, the criteria are set in the following manner: outer surface quality after cutting, forming of shavings, kinematic processes and dynamic processes.

The authors would like to thank the VEGA grant agency at the Ministry of Education SR for supporting research work and co-financing the projects: Grant work VEGA #01/0406/2003 with the title: "*Research concerning the machinability of stainless steels in automated production*" *and Grant work #01/3173/2006 with the title* "*Experimental investigation of cutting zones in drilled and milled stainless steels*".

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