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TURNING OF HIGH QUALITY ALUMINIUM ALLOYS WITH MINIMUM COSTS

Marko Reibenschuh, Franc Cus, Uros Zuperl

Original scientific paper

Turning is one of the most common metal cutting procedures used. To optimize such a cutting process, some adaptations must be made. Implementing tool wear conditioning and the use of dry cutting can significantly lower the production cost. This research focuses on the cost effectiveness of using dry cutting in comparison with the use of cutting fluids and the use of different tool geometry. A series of tests was conducted and in the end the results are given.

Keywords: *aluminium, cutting fluids, production costs, turning*

Tokarenje visoko kvalitetnih aluminijevih legura uz minimalne troškove

Izvorni znanstveni članak

Tokarenje je jedan od najčešće korištenih postupaka za rezanje metala. Da bi se optimizirao takav proces rezanja, potrebne su neke prilagodbe. Uređaj za nadzor trošenja alata kod suhog rezanja može značajno smanjiti troškove proizvodnje. Ovo istraživanje se fokusira na isplativost korištenja suhog rezanja u odnosu na korištenje tekućine za rezanje i korištenje alata s različitom geometrijom. Provedena je serija testova i na kraju su dani rezultati.

Ključne riječi: *aluminij, tekućina za rezanje, tokarenje, troškovi proizvodnje*

1 Introduction
Uvod

In the past, the manufacturing industry and scientific research focused on efficiency, precision, and high quality. Better quality, greater demand from consumers, tightened specifications and competition on the global scale - market increased efforts to produce better products, faster and cheaper regardless of production methods. The effects of these results were put aside; consequently the impacts of these actions are shown daily. The ecological and economical damage done to the human health and environment is immense. To reduce the effects of these actions, new materials and new methods are being used. Also the governments of many countries are issuing directives for lowering the costs and influence on the environment.

Aluminium alloys are widely used in the automotive, aircraft and shipbuilding industry. Different alloys, respectively different classifications, are being used for aluminium alloys. Examples are the 1xxx to 8xxx series, Tab. 1. There are currently eight different wrought alloy series, which are commonly referred to as 1 xxx-8xxx. The 1 xxx series aluminium alloys contain at least about 99,00 weight % aluminium per Aluminium Association standards. The 2xxx-7xxx aluminium alloys do not have the same Aluminium restriction, and are classified according to their main alloying element(s). The 2xxx aluminium alloys use copper, the 3xxx aluminium alloys use manganese, the 4xxx aluminium alloys use silicon, the 5xxx aluminium alloys use magnesium, the 6xxx aluminium alloys use magnesium and silicon, and the 7xxx aluminium alloys use zinc as their main alloying ingredient.

Table 1 *Standard characteristic of aluminium alloys – xxx series*
Tablica 1. *Standardne karakteristike aluminijevih legura – xxx serija*

Series	1xxx	2xxx	3xxx	4xxx	5xxx	6xxx	7xxx
Corrosion resistance	Excellent	Poor	/	Good	Good	Good	Good
Welding ability	limited	limited	limited	Good	Good	Good	Good
Major alloying element	/	Cu	Mn	Si	Mg	Si /Mg	Zn
Electrical and thermal conductivity	High	High	High	High	High	High	High

Each series of aluminium alloys has specific properties which must be considered during the development of new alloys and also during machining:
- Lower density in comparison to steel,
- Lower modulus of elasticity (approximately 1/3 of steel),
- Better thermal conductivity.

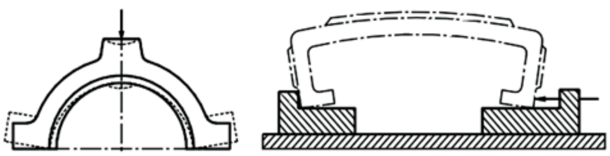


Figure 1 *Deformation of a work piece during clamping*
Slika 1. *Deformacija radnog komada kod stezanja*

Considering these properties, the aluminium alloys can be machined faster, but special care must be taken when thin wall work pieces are clamped – deformation and distortion, as shown in Fig. 1, must be avoided.

The cutting force needed to cut aluminium alloys is roughly 1/3 of the cutting force needed for cutting steel. Also the lubrication during the cutting procedure is a very important factor. The lubricants are used to control and aid the following:
- Cooling to dissipate the heat generated by friction during cutting,
- Cooling to minimize any effect on the metal's gauge or metallurgical properties,
- Preventing chips bonding to the tool surface,

- Removing chips from the point of machining,
- Maintaining the desired shape of the part,
- Friction reduction between the metal and the forming tools or dies,
- Lowering wear rate of dies and tooling.

The following types of lubricants are available:

- Cutting oils – straight or neat oils,
- Water soluble oils:
  - Synthetic lubricants,
  - Semi – synthetic lubricants,
  - Dry – film lubricants,
  - Chemically bonded agents.
- Gaseous fluids and gaseous-liquid mixtures.

All these lubricants can be applied as:

- Low – pressure flood application,
- High – pressure flood application,
- Trough – toll application,
- Mist application.

Most common pure cutting oil is used because of its superior ability to cool the cutting point on the work piece and on the tool. Also this method dissipates more energy per kilogram of lubricant.

The demand for parts, machined out of high tech materials is high. High quality and long life expectancy are the main goals. Also one good property is the resistance of aluminium to corrosion. Its disadvantage is the machinability. The chips, forming at machining (turning, milling, drilling…), are very soft and in a very short time they can damage the tool or the work piece by sticking to their surface and melting. In doing so, they can raise the temperature of the cutting tool or the work piece. Also, they can change the tool geometry and in doing so, disable the cutting ability of the tool. For machining such an alloy, dry cutting and cutting fluids can be used. Each of these procedures has its advantages and disadvantages.

1.1 Dry cutting
Suho rezanje

Recently, there has been an increasing interest in reducing or even eliminating the use of cutting fluids in machining. Dry cutting saves coolants and in doing so, it is more environment friendly. The exposure of operators to health risks is also minimized. Cutting without a coolant is also cheaper. But the cutting tool must be capable of handling and cutting such a material – its geometry and material must be adapted to aluminium. Also the cutting parameters for aluminium must be adapted – usually lower cutting speeds (maximum 2300 rev/min) and feed rates (from 0,02 to 1,1 mm) are used in comparison to steel alloys.

1.2 Use of cutting fluid
Uporaba tekućine za rezanje

On the other side, there is cutting with cutting fluid. There is a whole array of different product areas:

- Boron-free cutting fluid,
- Oil-free synthetic forming fluids,
- Amine and boron-free cutting fluid,
- Tube forming lubricant,
- Formaldehyde free cutting fluid,
- Tube bending lubricant and chemicals,
- Soluble cutting fluid,
- Metal cutting fluid,
- Ultra long life cutting fluid,
- Vanishing oils,
- Magnesium cutting fluid,
- Rust preventives,
- Ultra-hard water cutting fluid,
- Corrosion Inhibitor,
- …

In automotive industry, the cost for coolants and lubricants exceeds 16 % and is fast approaching 1/5th of the whole production costs. Comparing the cost for cutting tools, the cost for coolants already exceed the cost for tools. In high-volume machining, cutting tools present approximately 5 % of the total machining costs. Also the removal of the coolants is very costly and problematic. Not only are the coolants aggressive to human health, they are also aggressive to the environment. The cost for high quality coolants is nowadays in the range of 5000 €/m^3, [13, 15]. For emulsions the costs are significantly lower, about 270 €/m^3 – the low price is a consequence of mixing the concentrate with tap water in a 3-10 % ratio. Although the ratio can vary, depending on which property of the emulsion we want to use (cooling or lubrication), the ratio is in general from 3 – 10 %. The used coolants and lubricants have to be properly removed. For coolants the cost is about 110 €/m^3, for emulsions, the cost is 280 €/m^3. The costs for disposing emulsions are already bigger than the cost for buying a new one.

An extreme effect of coolants and lubricants is noticed in the ground, water and air pollution. Especially the public in USA, Japan, Australia and Germany is aware of that. In consequence, the governments of these countries are doing everything to lower the pollution.

Using specially developed oil for cooling the cutting tool and work piece is a very simple solution for lowering the temperature in the cutting zone, extending the tools' life expectancy and speeding up the production, [3, 4, 9, 10, 11, and 14]. But this application of coolant is not enough to assure small, short chips. For that purpose the cutting parameters need to be changed. Usually the cutting speed, feed rate and depth of cut are adapted. Many researchers are working on optimizing this parameters, among them Özel and Karpat [8] and Jurkovic et al., [16]. Researchers also search for new cutting materials and test them, Venkatesh et al. [12].

In most cases, the work piece material is the same and the cutting parameters are changed. In our case, for high rate production and large series, a manufacturer has decided to use such a material that can be turned on existing turning machines. Furthermore, the machines must be exploited to their maximum cutting speed and feed rate. In theory this is possible without further adaptations but in reality, this is harder to achieve. With some modifications to the procedure and cutting parameters the end result can come close to desired values. Using a method to optimize the work piece material brings us a step forward to this goal. Other methods used by Armarego and Samaranayake [1, 2] Cus and Zuperl [5, 6] and Karpat and Özel [7, 8] clearly show what can be achieved with the help of modern software combined with the proper hardware. Using artificial intelligence and applying hardware components to measure cutting force, temperature and sound, results in shorter production times and usually better surface quality.

Because of the coolant disadvantages, the main goal of the material manufacturers is to manufacture a material with the best possible ability for machining.

2 Test preparations
Priprema testova

The purpose of the test is to determine the best aluminium mixture for turning small parts whose diameter ranges from 10 to 20 mm. 20 mm was the maximum value for the stock part – work piece. All other values were lower. At the end of some tests the part had a maximum value of 10 mm. The main goal of the research was to determine the optimum aluminium mixture for short, small chips – these kinds of chips allow the fastest heat removal from the cutting zone – this is vital for aluminium alloys as they are very sensitive to high temperatures. If the chip stays too long on the same spot, it can weld to the work piece surface or to the cutting tool. In doing so, the temperature of the tool can dramatically rise and in the end it can dramatically fail - break.

The cutting parameters are adapted to the machine, which the work piece is going to be worked on. The cutting speed is adapted to Tab. 2, depending on the diameter of the work piece.

Table 2 *Cutting parameters during testing*
Tablica 2. *Parametri rezanja tijekom testiranja*

	Dry	Wet
Diameter of work piece	20 mm	20 mm
Cutting speed / m/min	22,29; 44,59; 56,52; 70,34; 87,92	140,7;
Feed rate / mm	0,02; 0,0315; 0,04; 0,05; 0,1; 0,11	0,02; 0,03; 0,05; 0,07; 0,1
Rake angle /°	6	6
Flank angle /°	6	6

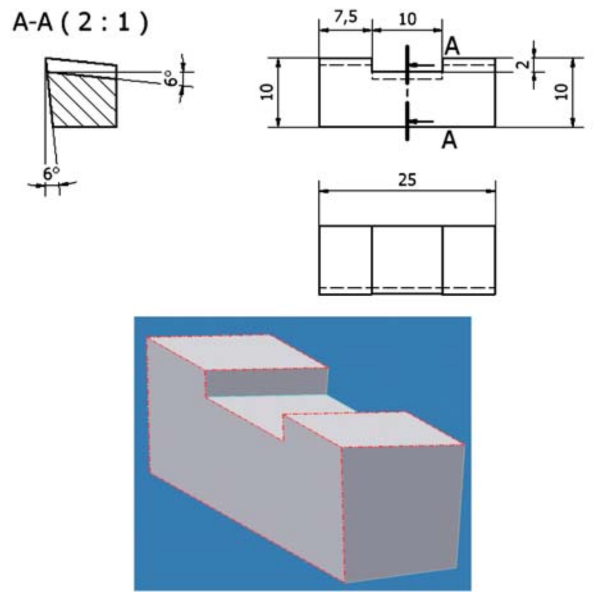


Figure 2 *Tool geometry*
Slika 2. *Geometrija alata*

The tests were conducted on a 24 kW turning machine with the option of dry cutting and the use of cutting fluids.

The cutting tool is a standard turning tool, adapted for our tests. Two different cutting tools were used, one with 25 and the other with 32 mm in width. Both tools had the sintered carbide for cutting material (P25/30). For tests, one tool was used as delivered from the manufacturer, the other one was ground to a form, shown in Fig. 2.

2.1 Cutting parameters
Parametri rezanja

The main problem or difficulty is always the decision on which procedure to choose and which cutting parameters to employ – use. One option is dry cutting, the other option is to apply cutting fluids. The main goals of high speed productions are:

- Shortening the production time and
- Lowering production costs.

Advantages of active liquid cooling are:

- Lowering the temperature of the cutting tool and work piece,
- Extending the tool durability – life expectancy,
- Reduction of contact time between tool and work piece,
- Lowering the heat load on the tool, work piece and machine centre.

Although the addition of cutting fluids improves some effects from cutting it also has two major disadvantages in direct comparison to dry cutting, thermal shock and material expenses (liquids, pumps, disposal of used liquids ...).

The use of dry cutting demands some modifications in order to achieve the same results as with the use of cutting fluids. These modifications affect the end quality and are easy to apply:

- Greater depth of cut,
- Greater feed rate per cutting tooth,
- Greater cutting speed, and
- Modified tool geometry.

All these steps, to improve the cutting procedure, result in greater tool and machine load, consequently greater power consumption and greater and faster tool wear.

For the first set of tests, dry cutting was chosen for the work piece diameter of 20 mm, cutting fluid was used only in the second set of tests with the work piece diameter of 20 mm.

Cutting speed and feed rate were adapted to those values, used on the specific machines – defined by the manufacturer. Tab. 2 represents used data.

3 Results
Rezultati

Turning procedure was conducted for a time period of 5 s. The length of the period was chosen to provide enough chips to measure and compare with other results. Tables 3 and 4 show the results from different cutting parameters – feed rate and cutting speed were changed. In the beginning of the test, very low, conservative values for feed rate and cutting speed were chosen. On behalf of the results, the cutting parameters were changed. During the dry cutting, the lowest value for feed rate was at 0,02 mm and the highest at 0,11 mm. The value for cutting speed ranged from 44,59 m/min. to 87,92 m/min. During the cutting with cutting fluid, the lowest value for feed rate was 0,02 mm and the highest was 0,1 mm. Because the cutting speed of 140,7 m/min. gave the best results in wet cutting, this speed was used during the whole second test.

3.1 Dry cutting results, ∅ 20 mm
Rezultati suhog rezanja, ∅ 20 mm

Tab. 3 shows that the first (1-6) tests were accomplished with the stock tool – without modifications to its geometry. The cutting speed and feed rate were the only parameters changed. The tests were all completed – none of the work pieces failed. The results show that the shortest chips were in test number 4 – in length, they measured from 6 - 8 mm.

The tests from number 7 to number 22 were completed with the modified tool, ground to the shape, Fig. 2. All tests were completed because the highest feed rate was not applied – in one case the highest feed rate was applied and the work piece broke off. The cutting speed and feed rate varied – because of the shape of the chip, additional combinations of cutting speed and feed rate were tested. The shortest chips were in test number 18 – the length of the chip ranged form 12 - 23 mm.

Table 3 *The shape of the chip and the cutting parameters of each test under dry conditions*
Tablica 3. *Oblik strugotina i parametri za svaki test kod suhog rezanja*

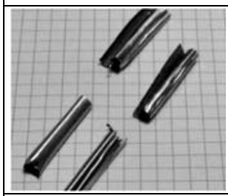
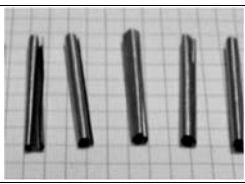
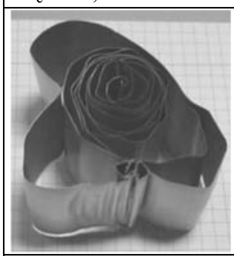
Stock tool	
1. f = 0,07 mm v_c = 44,59 m/min	2. f = 0,11 mm v_c = 56,52 m/min
	
3. f = 0,05 mm v_c = 56,52 m/min	4. f = 0,0315 mm v_c = 56,52 m/min
	
5. f = 0,0315 mm v_c = 70,34 m/min	6. f = 0,04 mm v_c = 56,52 m/min
	

Table 3 *The shape of the chip and the cutting parameters of each test under dry conditions (extension)*
Tablica 3. *Oblik strugotina i parametri za svaki test kod suhog rezanja (nastavak)*

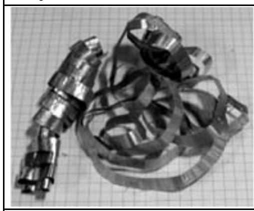
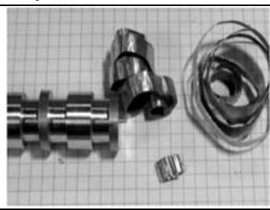
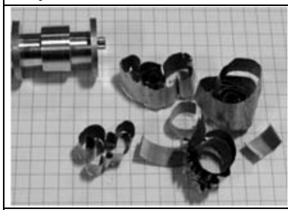
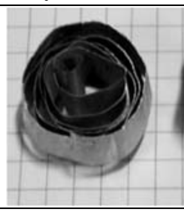
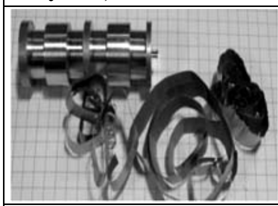
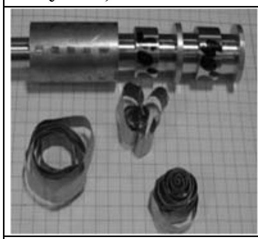
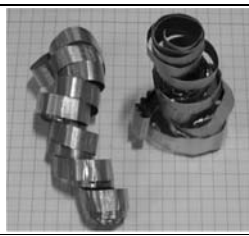
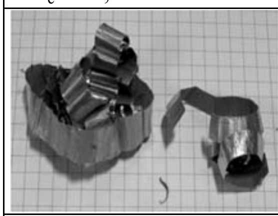
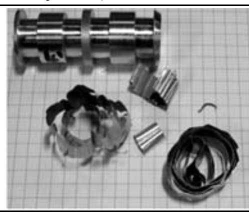
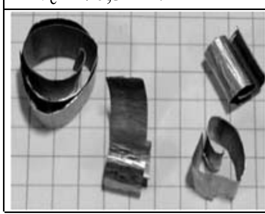
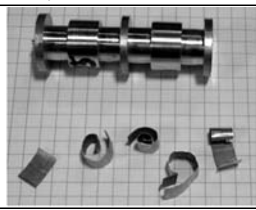
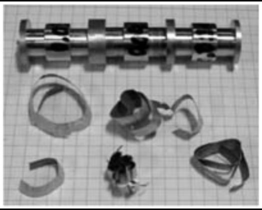
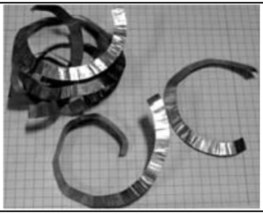
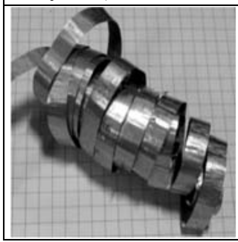
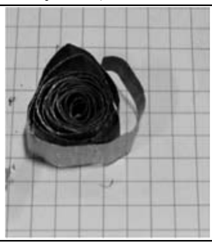
Modified tool	
7. f = 0,02 mm v_c = 56,52 m/min	8. f = 0,0315 mm v_c = 56,52 m/min
	
9. f = 0,04 mm v_c = 56,52 m/min	10. f = 0,05 mm v_c = 56,52 m/min
	
11. f = 0,02 mm v_c = 44,59 m/min	12. f = 0,0315 mm v_c = 44,59 m/min
	
13. f = 0,04 mm v_c = 44,59 m/min	14. f = 0,05 mm v_c = 44,59 m/min
	
15. f = 0,02 mm v_c = 70,34 m/min	16. f = 0,0315 mm v_c = 70,34 m/min
	
17. f = 0,04 mm v_c = 70,34 m/min	18. f = 0,05 mm v_c = 70,34 m/min
	

***Table 3** The shape of the chip and the cutting parameters of each test under dry conditions (extension)*
***Tablica 3.** Oblik strugotina i parametri za svaki test kod suhog rezanja (nastavak)*

Modified tool	
19. f = 0,0315 mm v_c = 87,92 m/min	20. f = 0,04 mm v_c = 87,92 m/min
	
21. f = 0,05 mm v_c = 87,92 m/min	22. f = 0,0315 mm v_c = 22,29 m/min
	

3.2 Cutting results with cutting fluid, ∅ 20 mm
Rezultati rezanja s uporabom tekućine, ∅ 20 mm

The first series of tests showed some good results. Considering these results, we decided to apply the same feed rate in the second series of tests, because other results are not good enough to proceed with them. Here, we used cutting fluid to remove the heat caused by the cutting procedure. The cutting speed was raised to pre-specified value of 140 m/min.

The tests (1-5) were conducted with the stock tool. The shortest chip was in test number 4 – the length of the chip ranged from 25 – 40 mm.

Tests from number 6 – 10 were accomplished with the pre-specified cutting speed. Test number 9 shows the best result. The chips in this test are the shortest, their length ranging from 22 – 45 mm.

***Table 4** Results of the second set of tests – with cutting fluid*
***Tablica 4.** Rezultati oblika strugotina kod mokrog rezanja*

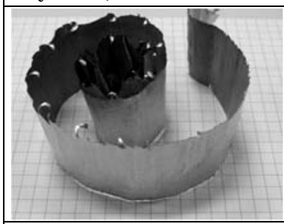
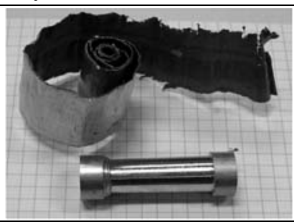
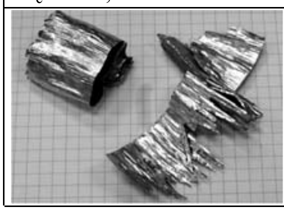
Stock tool	
1. f = 0,02 mm v_c = 140,7 m/min	2. f = 0,03 mm v_c = 140,7 m/min
	
3. f = 0,05 mm v_c = 140,7 m/min	4. f = 0,07 mm v_c = 140,7 m/min
	

***Table 4** Results of the second set of tests – with cutting fluid (extension)*
***Tablica 4.** Rezultati oblika strugotina kod mokrog rezanja (nastavak)*

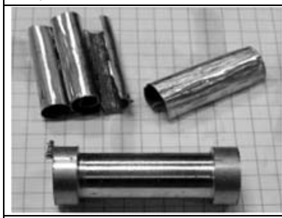
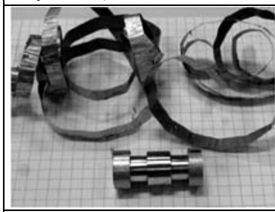
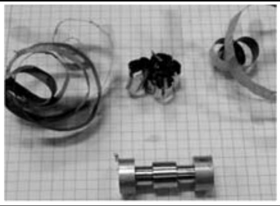
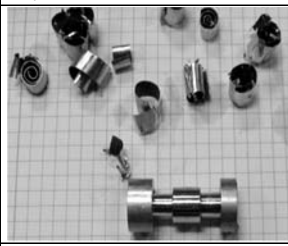
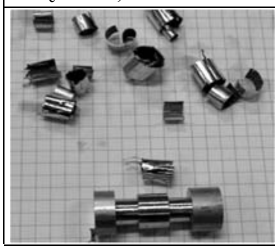
Stock tool	
5. f = 0,1 mm v_c = 140,7 m/min	
	
Modified tool	
6. f = 0,02 mm v_c = 140,7 m/min	7. f = 0,03 mm v_c = 140,7 m/min
	
8. f = 0,05 mm v_c = 140,7 m/min	9. f = 0,07 mm v_c = 140,7 m/min
	
10. f = 0,1 mm v_c = 140,7 m/min	
	

***Table 5** End results*
***Tablica 5.** Konačni rezultati*

Test/ No./ Tool	Dry cutting-chip length / mm	Wet cutting-chip length / mm	Cutting speed / m/min	Feed rate / mm
4/∅20 – stock tool	6 - 8	-	56,52	0,031
18/∅20 – mod. tool	12 - 25	-	70,34	0,05
4/∅20 – stock tool	-	25 - 40	140,7	0,07
9/∅20 – mod. tool	-	22 - 45	140,7	0,07

After the completion of the tests, a conclusion was made considering the results. Tab. 5 shows that the feed rate had the strongest impact on chip formation. The best chip formation was for feed rate at 0,07 mm and the cutting speed of 140 m/min and the addition of cutting fluid.

4 Conclusion
Zaključak

The results show the most useful cutting parameters for this type of alloy and the effect of cutting fluid. In a further test, the tool geometry will be adapted – the rake and flank angle will be changed according to the latest researches in this field. After reviewing some practical researches, the tool geometry must be adapted. For cutting aluminium alloys, the rake angle must be at least 6°, and can go up to 12°, in some cases to 20°. The cutting parameters feed rate and cutting speed are on the maximum of the machine centre output − these values will not be changed. In some operations, it is often better, when possible, to eliminate the cutting fluid and accept somewhat lower tool life and higher tooling costs. Although the costs for tools rise, it is still more cost efficient to use more tools than cutting fluids.

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Authors' addresses
Adrese autora

Marko Reibenschuh, asistent
Faculty of Mechanical Engineering
Smetanova 17, 2000 Maribor, Slovenia
Tel.: 00386 02 220 7606
e-mail: marko.reibenschuh@uni-mb.si

Prof. dr. Franc Cus
Faculty of Mechanical Engineering
Smetanova 17, 2000 Maribor, Slovenia
e-mail: franc.cus@uni-mb.si

Prof. dr. Uros Zuperl
Faculty of Mechanical Engineering
Smetanova 17, 2000 Maribor, Slovenia
e-mail: uros.zuperl@uni-mb.si