Int J Adv Manuf Technol (2014) 75:91–96
DOI 10.1007/s00170-014-6126-7

ORIGINAL ARTICLE

A new method to evaluate the machinability of difficult-to-cut materials

Xiangyu Wang · Chuanzhen Huang · Bin Zou · Hanlian Liu · Hongtao Zhu · Jun Wang

Received: 21 February 2014 / Accepted: 30 June 2014 / Published online: 12 July 2014

Abstract Machinability is a measure of ease with which a work material can be machined, and it is important in process planning and machining operations. Experiments of face milling four kinds of wrought superalloys were conducted at various cutting speeds from 30 to 90 m/min using coated cemented carbide tools. The tool life and tool failure modes were discussed, and two concepts of the cutting speed sensitivity and the critical speed at which the tool failure mode changes were presented. And then a new method to evaluate the machinability of difficult-to-cut materials was proposed. Based on this method, the machinability of the four kinds of superalloys was evaluated, and they could be ranked in such an order as GH605<GH4169<GH4033<GH2132.

Keywords Machinability evaluation · Superalloy · Tool life · Cutting speed sensitivity · Tool failure mode · Critical speed

1 Introduction

Machinability is a measure of ease with which a work material can be machined. It is related to all aspects of manufacturing process, such as product design, quality control, and especially, the process planning and machining operations [1, 2]. The machinability is an important consideration for engineers in materials selection, and it is the base of selecting cutting tools and optimizing machining parameters.

Many criteria for the machinability evaluation of work materials have been presented, for examples, tool life, cutting force, machined surface integrity, and dimensional accuracy. And it depends on manufacturer's interests and product requirements to choose the criteria. For instance, the tool life is widely used to evaluate machinability, while the surface integrity is a dominant criterion in finish machining.

In the past years, many researchers paid attention to the machinability evaluation of different materials. Some of them investigated the machinability of a specific material using a specific kind of cutting tool. For example, the machined surface quality has been used to evaluate machinability of 90MnCrV8 steel in high-speed milling using CVD-coated carbide insert, and they investigated the effects of cutting speed, tool diameter, and workpiece hardness on the roughness [3]. Davim and Figueira evaluated the machinability in hard turning of cold work tool steel (D2) with ceramic tools by evaluating specific cutting pressure, surface roughness, and flank wear [4]. Horng et al. conducted the machinability evaluation of Hadfield steel (SCMnH11) in hard turning with Al_2O_3/TiC ceramic tool on the basis of flank wear and surface roughness [5]. The above investigations mainly focused on the performance of a specific cutting tool on a specific material, and it was an optimization of cutting parameter rather than machinability evaluation of workpiece material. Some other researchers compared the machinability of different materials using direct comparison method or mathematical analysis methods. Arrazola et al. evaluated the machinabilities of Ti6Al4V and Ti555.3 by directly comparing their cutting forces, chip geometry, and tool wear, and found that Ti555.3 had a poorer machinability [6]. Kikuchi and Okuno evaluated the machinabilities of titanium, two titanium alloys (Ti-6Al-4 V and Ti-6Al-7Nb), and free-cutting brass by direct comparison of the cutting force, chips, and spindle motor current,

X. Wang · C. Huang (✉) · B. Zou · H. Liu · H. Zhu · J. Wang
Center for Advanced Jet Engineering Technologies (CaJET), School of Mechanical Engineering, Shandong University, 17923 Jingshi Road, Jinan 250061, People's Republic of China
e-mail: huangcz@sdu.edu.cn

X. Wang · C. Huang · B. Zou · H. Liu · H. Zhu · J. Wang
Key Laboratory of High-efficiency and Clean Mechanical Manufacture, Ministry of Education, Shandong University, Jinan, People's Republic of China

Table 1 The mechanical properties of the four kinds of superalloys

Material grades	Yield strength $\sigma_{0.2}$ (MPa)	Tensile strength σ_b (MPa)	Elongation (%)	Hardness (HRC)	Average grain size (Grade)
GH4169	1,093	1,295	14	42	8
GH605	342	876	35.5	29	6
GH2132	775	1,050	31	30	8
GH4033	595	890	14	38	6

and ranked them on the three criteria separately [7, 8]. Liu and Chen conducted an experimental study on the machinability of six kinds of wrought nickel-based superalloys, and compared them directly based on element contents, tool failure mode, and wear mechanism [9]. Venkata Rao and Gandhi used digraph and matrix methods to evaluate the machinability considering several machinability attributes and their relative importance, and proposed a universal machinability index [1]. Then, Rao proposed another global machinability index based on a combined TOPSIS and AHP method [2]. In these two papers, Rao used machining process output data from former research results [10, 11], and drew the similar conclusions. What is more, some researchers investigated the relationship between the mechanical properties and the machinability. Chen et al. investigated the influences of five workpiece mechanical and thermal parameters on machinability (cutting speed and cutting force) according to the analytical grey incidence process, and found that the hardness and tensile strength were two main factors [12]. Medvedeva et al. conducted a study on the influence of nickel content on machinability of a hot-work tool steel by evaluating tool life, cutting forces, and tool/chip interface temperature, and found its positive effect [13]. Besides, some researchers proposed some method especially for high-speed cutting, for example, Thakur et al. used chip compression ratio and shear angle to look into machinability of Inconel 718 in high-speed turning [14].

Although several machinability evaluation methods were proposed, there was an obvious shortage that almost all the evaluations were conducted at a specific cutting speed. However, the machinability is an inherent material performance, and it should be evaluated at a wide cutting speed range. In this paper, face milling experiments were conducted under various cutting parameters to evaluate the machinability of four kinds of wrought superalloys. The tool life and tool failure modes were analyzed, and a new method to evaluate the machinability was proposed.

Table 2 The face milling cutting parameters

Parameter	Value	Parameter	Value
V (m/min)	30, 45, 60, 75, 90	a_p (mm)	0.3
f (mm/tooth)	0.05, 0.1, 0.15[a]	a_e (mm)	55

[a] Feed rate for GH605 are 0.1, 0.15, and 0.2, because the workpiece roughness was bad and there was serious friction noise when the feed was 0.05 mm/tooth

2 Experimental procedures

The workpieces used in the face milling experiments were four kinds of wrought superalloys with the size of 150 mm× 110 mm×110 mm, and the properties of the workpieces are listed in Table 1.

The machining tests were carried out on DAEWOO ACE-V500 vertical machining center, and the cutting fluid was not used in this operation. A full factorial experimental design was adopted, and the cutting parameters are shown in Table 2. DIJET PVD TiAlN coated carbide inserts JC8015-ODHW606AEN were used i, and the cutter was OTC-06100-32R with a diameter of 100 mm. Only one insert was fixed on the cutter, and down milling was adopted. During the experiment, the flank wear was measured and recorded every 2 min with a digital microscope until the value of flank wear reached 0.3 mm or the tool were severely broken. Then, the tool wear or breakage morphology was observed using KEYENCE VK-X200K microscope.

The low cutting speed and feed rate resulted in a very short feed in 2 min, so the workpiece was pre-cut to eliminate the influence of entry and exit of the cutter. The schematic diagram of pre-cut workpiece is shown in Fig. 1. Section A was pre-cut and the experiment was conducted on section B, and then the section C was cut.

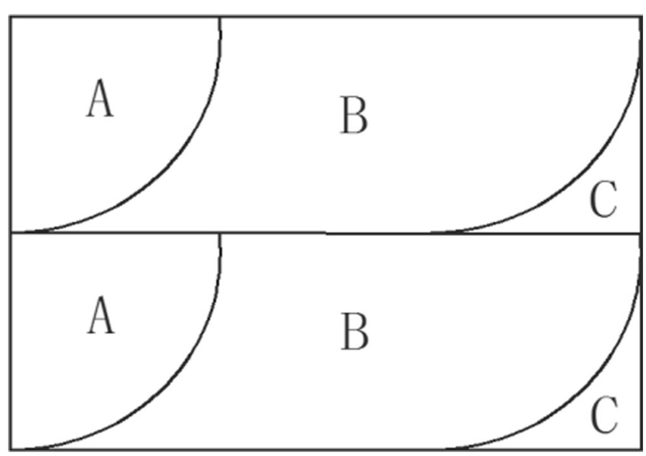

Fig. 1 Schematic diagram of workpiece

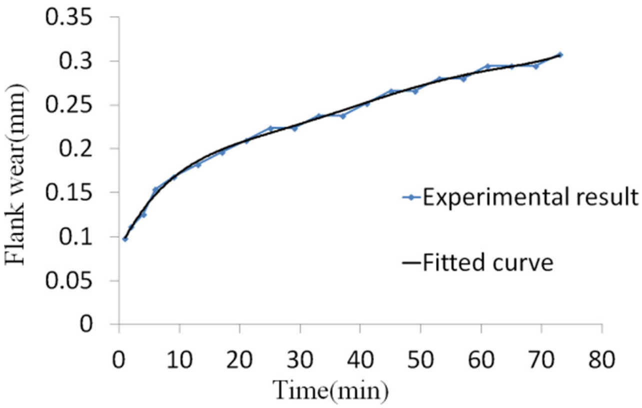

Fig. 2 Tool flank wear curve when cutting GH4169 at 30 m/min and 0.05 mm/tooth

3 Results and discussion

The recorded flank wear value was plotted against the milling time, and fitted as a cubic polynomial function of the time using the least square method. For example, the flank wear curve of the tool at 30 m/min and 0.05 mm/tooth when cutting GH4169 is shown in Fig. 2. When the flank wear value reached 0.3 mm or a serious breakage occurred at the cutting

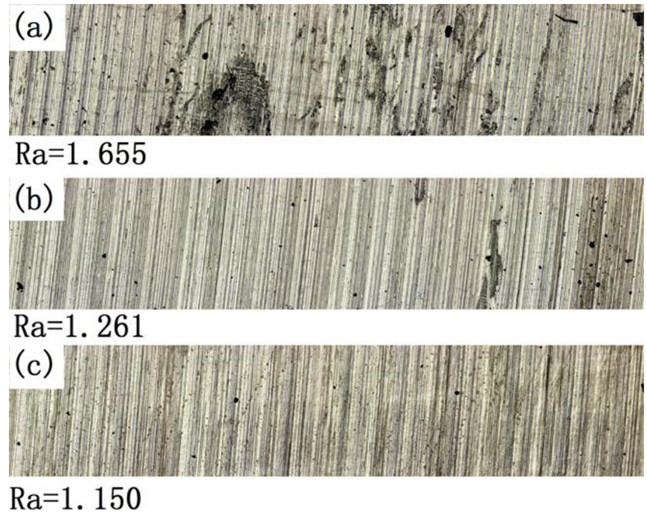

Fig. 4 Tool workpiece surface morphology of GH4169 at different feed when V=45 m/min. **a** f=0.05 mm/tooth. **b** f=0.10 mm/tooth. **c** f=0.15 mm/tooth

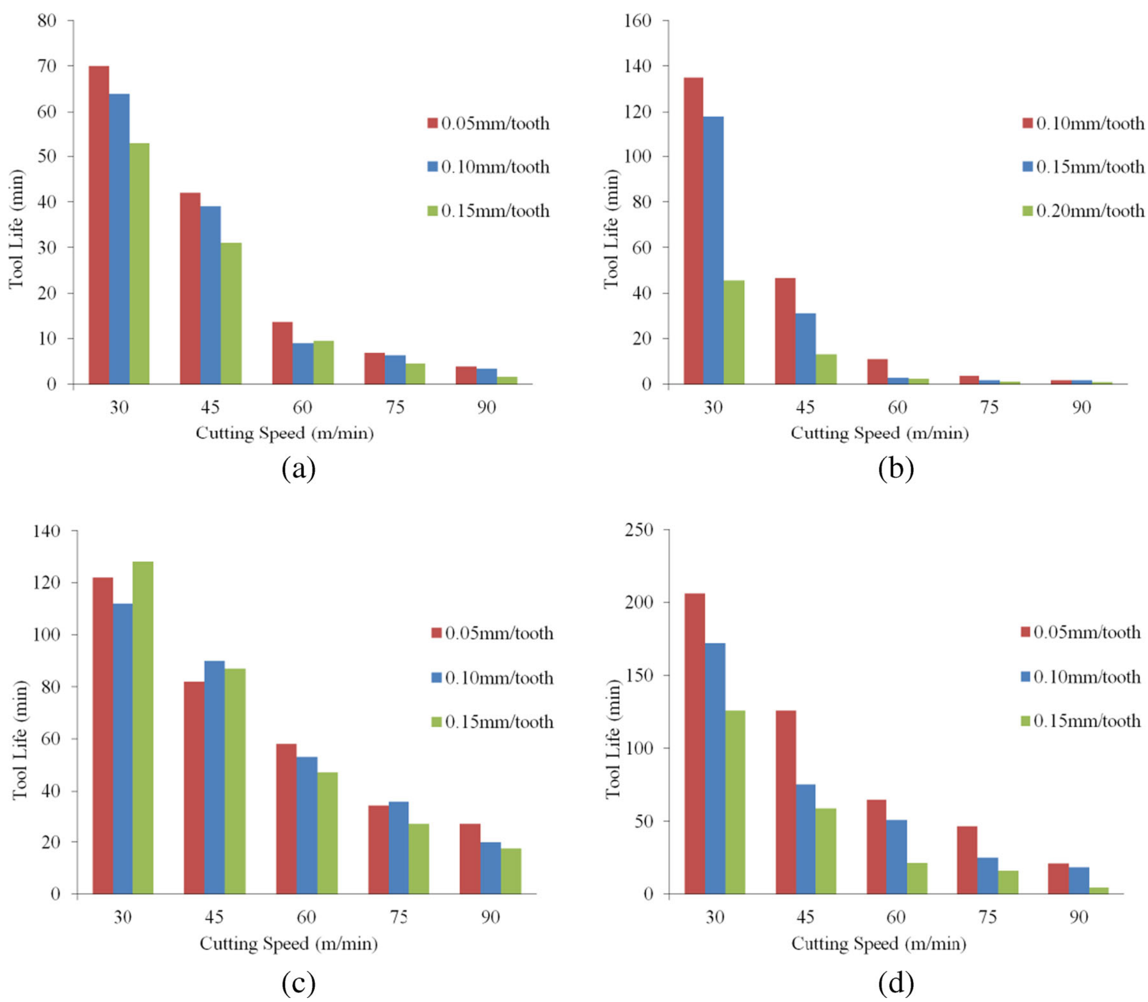

Fig. 3 Tool life at different cutting parameters when cutting. **a** GH4169. **b** GH605. **c** GH2132. **d** GH4033

Table 3 Values of m and n when f=0.1 mm/tooth, V_0=30 m/min

	GH4169	GH605	GH2132	GH4033
m	66.2	136.0	118.6	173.4
n	2.098	3.055	1.196	1.959

edge, the time was considered as the tool life. The tool life when cutting the four kinds of superalloys at different parameters is shown in Fig. 3.

It can be seen from Fig. 3 that the tool life when cutting four kinds of superalloys was short, especially at the high cutting speed. Based on traditional machinability evaluation criterion, the cutting speed which obtains a tool life of 60 min is used to compare with that of 1045 steel, or the tool life at a specific cutting speed is compared, and all the four superalloys are typically difficult-to-cut materials. Adopting these criteria, there was little difference in the machinability between GH4169 and GH605, and no difference between GH2132 and GH4033. But it can be seen from Fig. 3 that there are obvious differences when comparing in a wide cutting speed range. With the increase of the cutting speed, the tool life decreased drastically, so it is unreasonable to evaluate the machinability at a specific cutting speed or a specific tool life, and it is necessary to evaluate the machinability at various cutting speeds. For all the four superalloys, the tool life decreased greatly with the increase of the cutting speed, indicating that the tool life was very sensitive to the cutting speed. This can be easily explained by that the high speed resulted in a higher impact force and a higher temperature. To mathematically describe the sensitivity of the tool life to the cutting speed, the tool life of cutting four kinds of superalloys should be fitted as a function of the cutting speed, and an equation similar to the Taylor Formula was adopted, listed as Eq (1). Considering the tool life and material removal rate simultaneously, the feed was set at 0.10 mm/tooth. Also, the workpiece surface roughness when the feed was 0.10 mm/tooth was acceptable, for example, the workpiece surface morphology of GH4169 when the cutting speed was 45 m/min is shown in Fig. 4. When V_0 was set at 30, the values of m and n were calculated using the least square method, and are listed in Table 3.

$$T = m \bullet \left(\frac{V}{V_0}\right)^{-n} \tag{1}$$

It is obvious that m is the tool life at the cutting speed of V_0, and m could be the machinability index when adopting the traditional machinability evaluation criteria. A larger m indicates a better machinability. But when V_0 changed, m changed a lot accordingly, and the rank of the four superalloys' machinability changed at different cutting speeds. By contrast, n stays the same at different V_0. What is more, n could reflect the influence of the cutting speed on the tool life at a wide cutting speed range. Because the tool life when cutting difficult-to-cut material is sensitive to the cutting speed, n is named as the cutting speed sensitivity index. A large n means that the tool life is very sensitive to the cutting speed and it decreases

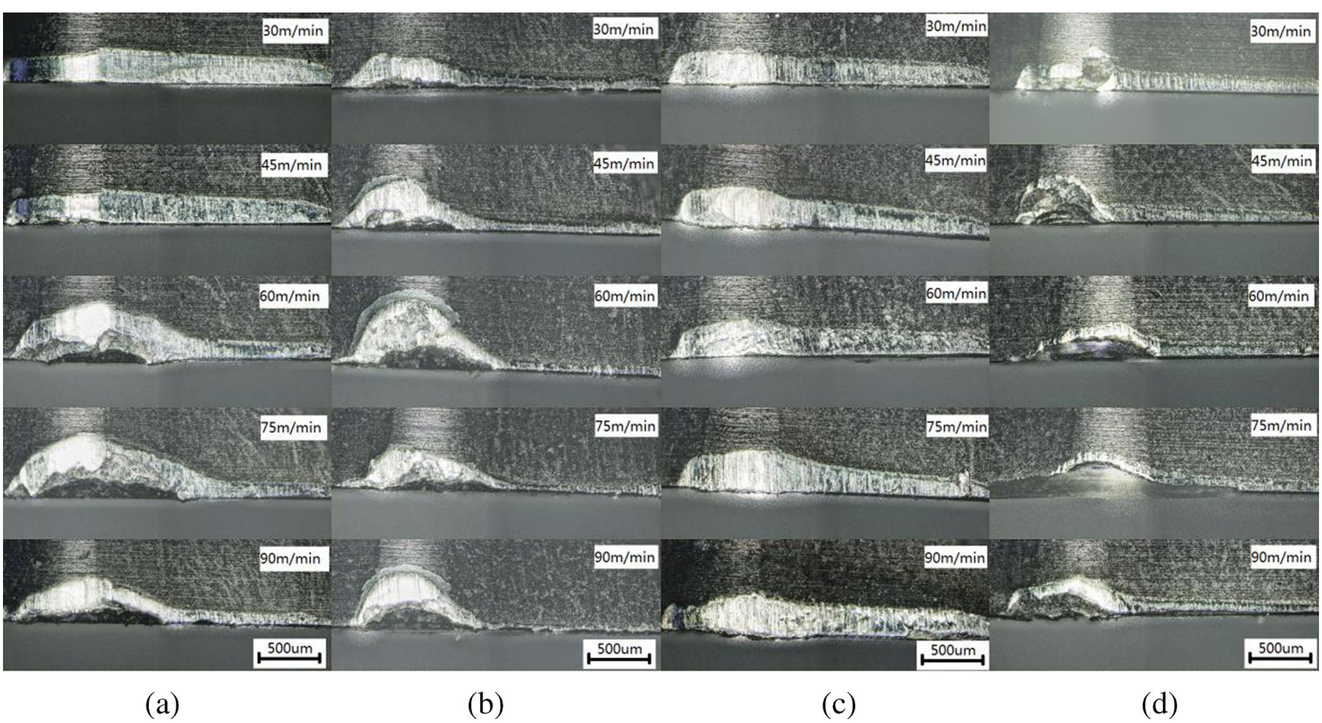

Fig. 5 Tool failure morphology at different cutting speeds when f=0.1 mm/tooth. **a** GH4169. **b** GH605. **c** GH2132. **d** GH4033

drastically when the cutting speed increases. In general, the tool life when cutting difficult-to-cut materials is short, and it decreases sharply with the increase of the cutting speed. So, it is reasonable to take the cutting speed sensitivity index as a new machinability evaluation index. In other words, a larger n indicates a worse machinability, and a small n indicated that the material could be machined at a wide range of cutting speed. Adopting this new criterion, the machinability of the four kinds of superalloys could be ranked in such an order as GH605<GH4169≈GH4033<GH2132.

It is well known that the tool failure mode varied when the cutting conditions changed. The tool failure morphology when cutting the four kinds of superalloys at different cutting speeds is shown in Fig. 5.

For GH4169, when the cutting speed was 30 m/min, the tool failure mode was uniform flank wear. But when the cutting speed increased, the tool breakage occurred, and the breakage became the main mode when the cutting speed reached 60 m/min. This was because the impact force during the milling process increased with an increase of the cutting speed, and the higher temperature resulting from the higher speed weakened the tools. Usually the superalloys are used in the extreme conditions, and the dimensional accuracy and surface integrity are highly demanded, so the unpredictable tool failure such as the serious breakage should be avoided. Because the tool breakage is a random phenomenon, it is a negative factor in machining difficult-to-cut materials. It can be seen from Fig. 5 that the tool failure mode changed from uniform flank wear to breakage when the cutting speed reached a critical value, and the critical speed when the tool failure mode changed was different for each workpiece material. A high critical speed meant that the material could be machined stably at a wide speed range. Taking into consideration the dimensional accuracy and surface integrity, a high critical speed implies a good machinability. So, the critical speed when the tool failure mode changed could be another machinability evaluation index. The critical speeds for GH4169, GH605, GH2132, and GH4033 were 60, 45, 90+. and 45 m/min, respectively. Adopting this evaluation criterion, the machinability of the four kinds of superalloys could be ranked in such an order as GH605≈GH4033< GH4169<GH2132.

Adopting the above two different criteria, it can be seen that GH605 was the most difficult to cut, and GH2132 was the easiest to cut. There were some differences referring to GH4169 and GH4033. The tool life was more sensitive to the cutting speed when cutting GH4169, but the critical speed when cutting GH2132 was higher. This contradiction could be easily solved if the different tool failure mechanisms could be understood. When cutting GH4169 at a high cutting speed, the tool failed in a short time, and it was typically early stage breakage. But it was fatigue breakage for GH4033 because it underwent a long time flank wear. So, it was obvious that GH4169 was more difficult to cut than GH4033. On the whole, it was reasonable to evaluate the machinability based on the variation of tool life and tool failure mode along with the increasing cutting speed, and the machinability of the four kinds of superalloys could be ranked in such an order as GH605<GH4169<GH4033<GH2132.

4 Conclusions

In this paper, the experimental studies for facing milling of four kinds of wrought superalloys with cemented carbide coated tools were conducted. The conclusions can be summarized as follows:

The tool life was short when machining superalloys, and it was greatly sensitive to the cutting speed. The cutting speed sensitivity index was proposed to evaluate the machinability, and a higher n indicated a poorer machinability.

The tool failure mode changed from uniform tool flank wear to tool breakage when the cutting speed increased. The critical speed when the tool failure mode changed was also suitable to evaluate the machinability. The higher the critical speed, the better the machinability.

Based on the above two criteria, the machinability of the four kinds of superalloys could be ranked in such an order as GH605<GH4169<GH4033<GH2132.

Acknowledgments The work is supported by National Natural Science Foundation of China (51005136 and 51175305).

References

1. Venkata Rao R, Gandhi O (2002) Digraph and matrix methods for the machinability evaluation of work materials. Int J Mach Tools Manuf 42:321–330. doi:10.1016/S0890-6955(01)00133-X
2. Venkata Rao R (2005) Machinability evaluation of work materials using a combined multiple attribute decision-making method. Int J Adv Manuf Technol 28:221–227. doi:10.1007/s00170-004-2348-4
3. Ekinović S, Dolinšek S, Begović E (2005) Machinability of 90MnCrV8 steel during high-speed machining. J Mater Process Technol 162–163: 603–608. doi:10.1016/j.jmatprotec.2005.02.178
4. Davim JP, Figueira L (2007) Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques. Mater Des 28:1186–1191. doi:10.1016/j.matdes.2006.01.011
5. Horng J-T, Liu N-M, Chiang K-T (2008) Investigating the machinability evaluation of Hadfield steel in the hard turning with Al2O3/TiC mixed ceramic tool based on the response surface methodology. J Mater Process Technol 208:532–541. doi:10.1016/j.jmatprotec.2008.01.018
6. Arrazola P, Garay A, Iriarte L, Armendia M, Marya S, Le Maître F (2009) Machinability of titanium alloys (Ti6Al4V and Ti555.3). J Mater Process Technol 209:2223–2230. doi:10.1016/j.jmatprotec.2008.06.020
7. Kikuchi M, Okuno O (2004) Machinability evaluation of titanium alloys. Dent Mater J 23:37–45

8. Kikuchi M, Okuno O (2004) Machinability evaluation of titanium alloys (Part 2)—analyses of cutting force and spindle motor current. Dent Mater J 23:621–627
9. Liu G, Chen M (2006) Experiment study on machinability of six kinds of wrought nickel-based superalloys. Mater Sci Forum 532–533:444–447. doi:10.4028/www.scientific.net/MSF.532-533.444
10. König W, Erinski D (1983) Machining and machinability of aluminium cast alloys. CIRP Ann Manuf Technol 32:535–540. doi:10.1016/S0007-8506(07)60180-2
11. Enache S, Strâjescu E, Opran C, Minciu C, Zamfirache M (1995) Mathematical model for the establishment of the materials machinability*. CIRP Ann Manuf Technol 44:79–82. doi:10.1016/S0007-8506(07)62279-3
12. Chen Y, Yu A, Wang M (2006) Determining the influence of property parameters on metal machinability via analytical grey incidence process. Manuf Technol Mach Tool 9:61–64 (in Chinese)
13. Medvedeva A, Bergström J, Gunnarsson S, Krakhmalev P, Nordh LG (2011) Influence of nickel content on machinability of a hot-work tool steel in prehardened condition. Mater Des 32:706–715. doi:10.1016/j.matdes.2010.07.037
14. Thakur DG, Ramamoorthy B, Vijayaraghavan L (2009) Machinability investigation of Inconel 718 in high-speed turning. Int J Adv Manuf Technol 45:421–429. doi:10.1007/s00170-009-1987-x