Effect of Residual Stresses in Surface Layer of Nickel-Based Alloy—Inconel 718 on the Safety Factor of Construction

Joanna Krajewska-Spiewak and Jozef Gawlik

Abstract Characteristics of the surface layer of difficult-to-cut materials have been presented in the article. Residual stresses generated in the material during machining process can be distinguished among many other properties of the surface layer. The main goal of the research was to determine the influence of peripheral milling on residual stresses state in the surface layer of the workpiece made out of Inconel 718. In order to determine safety factor of construction (based on stochastic dependence), residual stresses and exploitation stresses were taken into account.

Keywords Inconel 718 · Residual stresses · Safety factor of construction

1 Introduction

Development of new constructions is associated among others with increasing demand for new engineering materials. These materials, in general, belong to the group of difficult-to-cut materials and are most commonly used in following types of industries: aerospace, maritime, petrochemical, and biomedical engineering. The increasing demand of these materials is justified through their unique properties, which include high strength at relatively low density, creep resistance, and resistance to fatigue failures.

Ezugwu in his work [1] suggested the division of difficult-to-cut materials into four main groups: titanium-based alloys, nickel-based alloys, ceramics, and ferrous alloys. Additional type of material (composite materials) has been added to this division which is presented on Fig. 1.

J. Krajewska-Spiewak (✉) · J. Gawlik
Cracow University of Technology, Cracow, Poland
e-mail: jkspiewak@mech.pk.edu.pl; jgawlik@mech.pk.edu.pl

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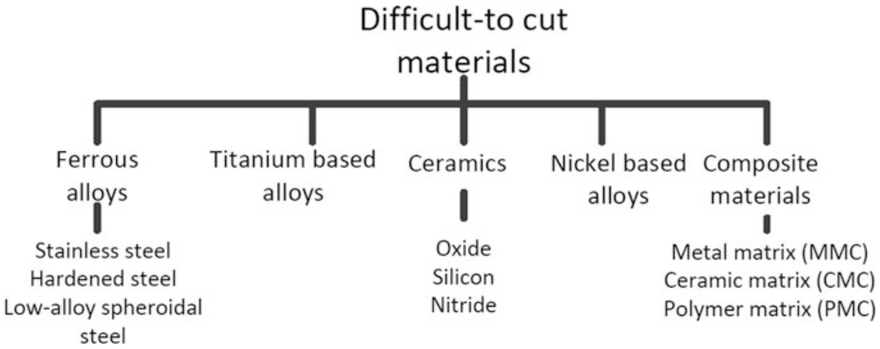


Fig. 1 Division of difficult-to-cut materials

2 The Characteristics of the Surface Layer Formed in the Cutting Process

Machining is an oriented and controlled process of cracking which is accompanied by progressive separation of the material in form of the chip with the use of wedge blade [2]. The cutting tool is a carrier of focused, external mechanical energy. The energy inside the material increases with the increase of plastic deformation. Crystal lattice is subjected to the increasing value of plastic deformation which alters properties of the workpiece.

During machining process, new stress state is generated which results in energy changes in the cutting zone. Stresses which are present in the material during external load and stresses present in the material in the absence of the influence of external forces can be distinguished [3]. Another division of stresses is based on the area of size in which they balance. According to Davidenkov's classification, stresses can be divided into:

- Macro-residual stresses (1st type of RS) appear in the area where their size is compared with the size of the workpiece. The existence of these stresses can be determined based on the displacement of diffraction lines in proper direction.
- Micro-residual stresses (2nd type of RS) appear in the area where their size is compared with the size of the grain. These residual stresses can be further divided into oriented residual stresses which arise as a result of oriented plastic deformation, and they cause an angular shift of diffraction lines. Unoriented residual stresses cause diffraction line broadening.
- Sub-residual stresses (3rd type of RS) appear in the area of the few atomic distances. The force and moment equilibrium exist in sufficiently large parts of a crystallite. These stresses are caused by numbers of deformations in crystal lattice (e.g., delamination and dislocations).

Stresses can be also distinguished based on the cause of their formation. Thereby, following types of stresses can be given: mechanical, thermal, and structural. Structural stresses arise from volumetric changes [4, 5]. They are generally caused by phase transitions and are determined by temperature and time. In case of increased specific volume, compressive stresses are present, otherwise tensile stresses occur. The uneven heating or cooling process of particular layers of the material leads to thermal stresses. After reaching a temperature below core temperature, compressive residual stresses are formed, while tensile stresses occur inside of the core. During machining process, mechanical stresses arise as a result of uneven deformation of the surface layer of the workpiece.

3 Impact of Cutting Conditions on Stress State in the Surface Layer of Inconel 718

Research was carried out on samples made out of nickel-based alloy—Inconel 718 through the wide range of its industrial applications. The main goal of the research was to determine the influence of peripheral milling on residual stresses state in the surface layer of the workpiece. During machining process, cutting forces were recorded by a Kistler three—component piezo dynamometer. The scheme of the workstation is presented on Fig. 2. The course of cutting forces was registered to correlate the obtained data with calculated values of residual stresses. After milling process, residual stresses were determined by X-ray diffractometer. Measurements were performed at the Institute for Sustainable Technologies—National Research Institute in Radom.

Table 1 presents scheme of the research program, while Table 2 contains ranges of variable parameters during milling process of Inconel 718.

The values of calculated residual stresses are presented in Table 3. Residual stresses were identified in samples made out of nickel-based alloy—Inconel 718 after peripheral, down-cut milling. Research was carried out on a diffractometer (Brucker's company), where σ_r—stresses calculated in the parallel direction toward milling process, σ_p—stresses calculated in the perpendicular direction toward milling process.

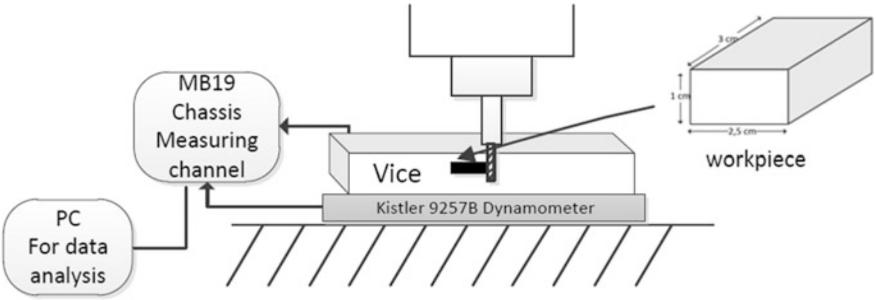


Fig. 2 Scheme of the work station and dimensions of the test sample [6]

Table 1 Scheme of the research program

No.	Code		
	x1	x2	x3
1.	−1	−1	−1
2.	+1	−1	−1
3.	−1	+1	−1
4.	+1	+1	−1
5.	−1	−1	+1
6.	+1	−1	+1
7.	−1	+1	+1
8.	+1	+1	+1
9.	$-\alpha$	0	0
10.	$+\alpha$	0	0
11.	0	$-\alpha$	0
12.	0	$+\alpha$	0
13.	0	0	$-\alpha$
14.	0	0	$+\alpha$
15.	0	0	0

Table 2 Variable cutting parameters used during milling process

$\alpha = 1.215$	Rotation speed n (rot/min) x_1	Feed f (mm/min) x_2	Depth of cut a_p (mm) x_3
$-\alpha$	955	100	0.2
−1	1485	280	0.35
0	1978	550	0.5
+1	2470	820	0.65

Carried out research confirms that a texturization of crystal lattice occurs in the surface layer during machining process in the direction of feed motion. Tensile stresses occurred in the surface layer of nickel-based alloys after milling.

The function of the research object was developed in order to determine the dependence between cutting parameters and residual stresses. Second degree of a polynomial function was created with interaction for three input parameters (v_c, f, and a_p). Obtained results are shown in a graphical form in Figs. 3, 4, and 5.

4 Safety Factor in Terms of Construction Reliability

Heterogeneity of the structure of materials, dispersion of values of strength characteristics, and instability of exploitation conditions are factors which justify consideration of safety factor of construction. Based on the research developed by Loladze [7] and Betanelego [8], safety factor (ϑ) can be presented as followed:

Table 3 Calculated stresses values generated in the surface layer of Inconel 718 [6]

No.	σ_r (MPa)	σ_p (MPa)	No.	σ_r (MPa)	σ_p (MPa)	No.	σ_r (MPa)	σ_p (MPa)
N1-1	545	439	**N33-1**	639	618	**N6-1**	352	199
N1-2	582	452	**N33-2**	706	654	**N6-2**	549	370
N1-3	588	547	**N33-3**	737	693	**N6-3**	611	448
N1-4	604	558	**N33-4**	680	640			
N11-1	489	376	**N4-1**	833	792	**N66-1**	703	658
N11-2	369	369	**N4-2**	890	813	**N66-2**	893	755
N11-3	365	365	**N4-3**	850	804	**N66-3**	870	724
N11-4	425	346	**N4-4**	795	815			
N2-1	677	720	**N44-1**	986	928	**N7-1**	544	418
N2-2	856	820	**N44-2**	1002	933	**N7-2**	536	375
N2-3	841	827	**N44-3**	919	860	**N7-3**	549	393
N2-4	733	774	**N44-4**	956	904	**N7-4**	625	462
N22-1	767	762	**N5-1**	719	693	**N77-1**	585	747
N22-2	822	766	**N5-2**	721	712	**N77-2**	823	803
N22-3	770	773	**N5-3**	486	475	**N77-3**	845	837
N22-4	750	730	**N5-4**			**N77-4**	820	816
N3-1	513	546	**N55-1**	538	564	**N8-1**	766	733
N3-2	703	615	**N55-2**	820	748	**N8-2**	814	716
N3-3	638	597	**N55-3**	689	594	**N8-3**	786	734
N3-4	550	568	**N55-4**	674	626			

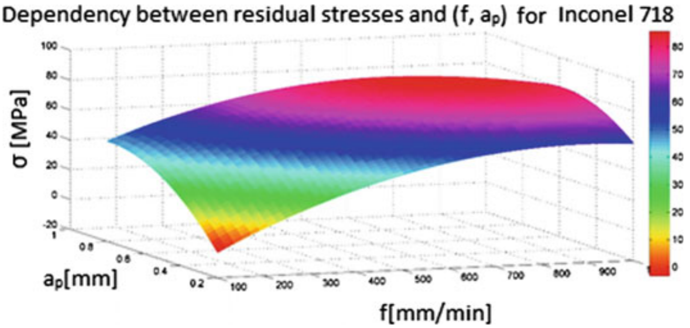


Fig. 3 Relationship between residual stresses and variable values of cutting parameters—feed and depth of cut (f, a_p) at constant cutting speed v_c = 62.1 [m/min] [6]

$$\vartheta = \frac{X_\sigma}{X_g} \tag{1}$$

where X_σ—determines the stress state in the material; X_g—determines the limit of ultimate strength of the material.

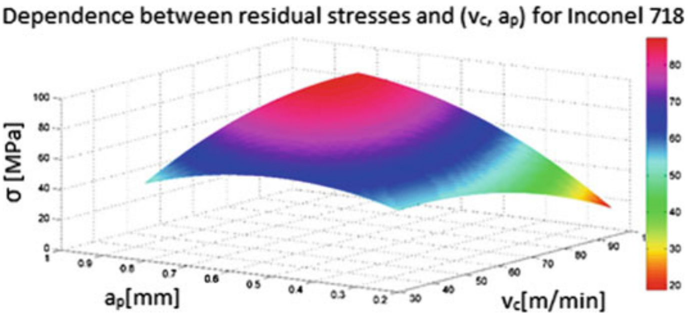


Fig. 4 Relationship between values of residual stresses and variable values of cutting parameters—cutting speed and depth of cut (v_c, a_p) at constant feed f = 550 [mm/min] [6]

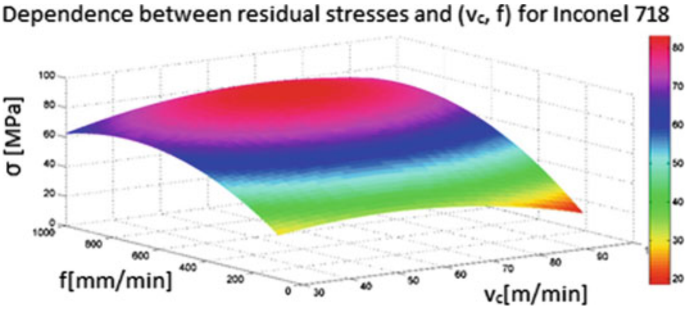


Fig. 5 Relationship between residual stresses and variable values of cutting parameters—cutting speed and feed (v_c, f) at constant depth of cut a_p = 0.5 [mm] [6]

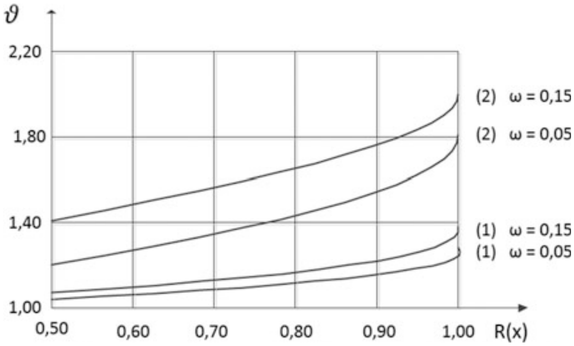
Strength characteristics of construction materials can be usually described by normal distribution. For a given quantile percentage (γ), the safety factor of the construction can be presented as followed:

$$\vartheta = \frac{1 - \omega_\sigma \cdot \gamma_R}{1 - \omega_d \cdot \gamma_{1-R}} \tag{2}$$

where $\omega_\sigma = \frac{D_{X_\sigma}}{X_{\sigma_s}}$—variation coefficient of stresses $\omega_d = \frac{D_{X_g}}{X_{g_s}}$—variation coefficient of the limit of ultimate strength of the material; γ_{R}- R—quantile percentage of normalized normal distribution and γ_{1-R} (1−p) quantile percentage of normalized normal distribution for determined level (p) of construction reliability (s); D_{X_σ}—standard deviation of stresses dispersion and D_{X_g}—standard deviation of the limit of ultimate strength of the material; X_{σ_s} average value of stresses and X_{g_s}—average value of the ultimate strength of the material.

The analysis of Eq. 2 indicates the safety factor of the construction that strongly depends on the dispersion of mechanical properties of the material and

Fig. 6 Dependence between safety factor (ϑ); reliability level (R); and coefficient of variation ω for two values of probability (p) of achieving assumed reliability (R); 1 $p = 0.90$; 2: $p = 0.975$



assumed/established level of construction reliability [9, 10]. To simplify (the model, the calculations), the authors assumed $\omega = \omega_\sigma = \omega_d$. Figure 6 shows the change of safety factor ϑ.

The results obtained from carried out research show that residual stresses arise after machining process and are present on the surface layer of the workpiece. These stresses affect the behavior of the element and they have an impact on the construction reliability. Stresses arise in the material as a result of external load. Generated residual stresses can add up and cause number of undesired effects (e.g., delaminations, cracing, tribological wear). Therefore, residual stresses should be taken into account during determination of safety factor.

With the use of chi-square test χ^2 authors demonstrated that in significance level equal to $\alpha = 0.05$, there is no reason to reject the hypothesis of the normal distribution of residual stress in the surface layer of Inconel 718 alloy. The dependence of safety factor takes the following form:

$$\vartheta = \frac{1 - \omega_{\sigma_w} \cdot \gamma_R}{1 - \omega_d \cdot \gamma_{1-R}} \tag{3}$$

where $\omega_{\sigma_w} = \frac{D_{X_\sigma} + D_{X_r}}{X_{\sigma_s} + X_{\sigma_r}}$—variation coefficient of combined stresses in a material, (X_σ) exploitation stresses, (X_r) residual stresses, D_{X_r}—standard deviation of residual stresses and X_{σ_r}—average value of residual stresses.

5 Conclusions

Multi-blade milling process of Inconel 718 alloy generates residual stresses in formed surface layer of the workpiece. The possibility of residual stresses summation must take into account during strength calculations when structures are subjected to external loads at the allowable level. Therefore, in order to ensure reliable operation of construction determination of the proper safety factor is necessary.

References

1. Ezugwu, E.O.: High speed machining of aero-engine alloys. J. Braz. Soc. of Mech. Eci. Eng. **XXVI**(1), (2000)
2. Dornfeld, D.: Process monitoring and control for precision manufacturing. Prod. Eng. **6**, 29–34 (1999)
3. Burakowski, T.: Areology, Theoretical basics (in Polish) Scientific Publishing of the Institute for Sustainable Technologies—PIB 2013
4. Radziejewska, J., Skrzypek, S.J.: Microstructure and residual stresses in surface layer of simultaneously laser alloyed and burnished steel. J. Mater. Process. Technol. **209**, (2009)
5. Toshiaki, S., Hiroyuki, S., Masaomi, T.: Development of a new tool to generate compressive residual stress within a machined surface. Int. J. Mach. Tools Manufac. **44**, (2004)
6. Krajewksa-Śpiewak, J.: Identification of the properties of surface layer of difficult-to-cut materials (in Polish). Dissertation, Cracow University of Technology, (2016)
7. Stakhniv, N.E., Devin, L.N.: The study of wear of cutting tools of cBN-based composite material and the influence of tool wear on cutting forces in turning hardened steel. J. Superhard Mater. **33**, 129 (2011)
8. Wang, P., Gao, R.X.: Stochastic tool wear prediction for sustainable manufacturing. Procedia CIPR 48, (2016)
9. Gawlik, J., Karbowski, K.: Forecasting of the wear state of the cutting tools in the cutting procecss (in Polish). Published by Cracow University of Technology. Monograph No. 66, (1998)
10. Odelros, S.: Tool wear in titanium machining. Uppsala University, (2012)