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ANALYSIS OF CUTTING FORCES IN END MILLING OF MULTI-LAYERED FUNCTIONALLY GRADED METAL MATERIAL

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Abstract: *Machining of functionally graded metal materials is an important operation in their integration into automotive tool making industry. Effective machining of these materials with changing properties requires detail knowledge of cutting forces which may result excessive product damage. Therefore, in this research, an experimental investigation was carried out to realize the machinability behavior of the four-layered functionally graded metal material in terms of the nature of the cutting force generated while performing the machining operation. A dynamometer was used to measure the actual cutting forces, which were graphically represented by diagrams depending on the angle of rotation of the cutting tool. The machining of 16MnCr5/316L four-layered metal material, manufactured by the laser engineered net shaping (LENS) process, was performed with a solid carbide ball-end mill. The influence of LENS process parameters, machining parameters and hardness and /or thickness of the deposited layers on resultant maximum cutting forces has been investigated in the analyses. The results were graphically represented.*

Key words: *cutting forces, end-milling, multi-layered metal material, LENS.*

1. INTRODUCTION

Multi-layered functionally graded metal materials are modern generation of flexible workpieces consisting of only one material deposited in several layers on a basis material.

The multi-layered functionally graded metal materials are manufactured by the very well-known laser engineered net shaping (LENS) process which was developed by Sandia National Laboratories. LENS uses a laser power in an airtight, argon environment to fuse metal powders into three-dimensional structures layer by layer.

Conventional machining techniques are not equal to adjust to the continuously changing workpiece structure of functionally graded metal materials.

Due to unknown distribution of the material properties and its inhomogeneous structure, offline analysis of cutting forces must be employed to determine the most efficient machining parameters.

Therefore, there is a necessity to analyze precisely the cutting forces in milling of these materials. The ability to comprehence the cutting forces is essential for selecting machining parameters that would result in more efficient machining. Knowing the cutting forces is fundamental for understanding the cutting processes and optimizing the milling process [1].

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The literature review revels the lack of knowledge about the machinability of the multi-layered functionally graded metal materials. For such advanced materials, it is difficult to gather data related to the influence of the LENS process parameters on the produced cutting forces, flank wear, and surface roughness. Published research relating to cutting force analysis for these materials is extremely scarce.

There are a few studies about the cutting force analysis of difficult-to-machine metal deposited materials, such as nickel-based alloys, titanium alloys, and composites. M´Saoubi [2] provided industrial perspectives in the context of machinability of specific alloys used in aerospace applications. He stated that the machinability of aerospace materials should be considered in much broader terms than machining tests that are directed at the tool performance/material removal rates. A group of researchers carried out mechanical [3] and machinability [2] assessment of a nickel-based superalloy (Inconel 718) in machining operations. Shokrani et al. [4] have reviewed and identified difficult-to-machine materials such as alloys used in the aerospace, nuclear and medical industries. Koyilada et al. [5] performed an evaluation of machinability characteristics of Nimonic C-263 using chemical vapour deposition (CVD) and physical vapour deposition (PVD) coated tools. Dong et al. [6] studied the chip formation during machining of nickel-based alloy Inconel 718 by observing chip metallographic graph.

In this research, an experimental investigation of cutting forces generated while performing the machining operation was carried out to realize the machinability behavior of the four-layered metal material.

2. EXPERIMENTAL SET-UP

To analyze cutting conditions in milling of functionally graded multi-layered metal materials, experimental results according to the five step procedure were obtained:

1. Nine four-layered functionally graded metal workpieces with dissimilar layer thicknesses were produced. LENS process parameters at three levels are indicated in Table 1.
2. Thickness d and hardness HV of deposited layers were measured.
3. The impact of LENS process parameters on the HV and d of the manufactured layers was examined.
4. A total of 243 machining tests were carried out to obtain cutting forces in three directions (Table 2); 27 tests were conducted on each workpiece. Three machining factors at three levels are indicated in Table 1. Each test was repeated three times under the same operating parameters.
5. The results of measured cutting forces were analysed and prepared for ANN training.

The machining experiments were carried out on the CNC machine tool (HELLER BEA02), under dry cutting conditions. The cutting forces were measured with a Kistler (Type 9257) piezoelectric dynamometer in the feed Fx, normal Fy and axial directions Fz. The dynamometer expresses some limitations since it is conditioned by the vibration of the surrounding system and by the transducer's natural frequency [1]. These parameters could affect the measurement accuracy when measuring cutting forces in high-speed machining. Relevant distortions of cutting force signals are not experienced if low tooth passing frequencies are used [1]. The cutting force measurements experiment in this research showed no need for dynamic compensation at employed low tooth passing frequencies (133 Hz). However, to cleanse measured force signals of possible errors induced by vibrations of the surrounding systems, a dual mode charge amplifier (Type 5001) with a low pass filter of 1 kHz cut-off frequency was used.

Table 1

LENS process parameters and appurtenant number of machining test

LENS experiment	*P* [W]	*c* [mm/s]	Machining test no. (n; f; A_D ; Θ)
1	300	30	1 to 27
2	300	48	28 to 54
3	300	60	55 to 81
4	380	30	82 to 108
5	380	48	109 to 135
6	**380**	**60**	**136** to **162**
7	400	30	163 to 189
8	400	48	190 to 216
9	400	60	217 to 243

The used filter is a one pole passive filter with second order Butterworth characteristic.

The low pass filter is set to about one-third of the natural frequency of the dynamometer.

The analogue force signal is then output to an NI 925A board control by the Labview software. To avoid the distortion, the first natural frequency of the dynamometer has to be at least 3 times higher than the cutting frequency.When the spindle speed is 4000 min^{-1} using the 2-flute end mill, the cutting frequency is 133 Hz. The natural frequency of the dynamometer should be therefore higher than 400 Hz to measure cutting force signals at the spindle speed of 4000 min^{-1}. The frequency bandwidth of Kistler 9257 dynamometer is, therefore, adequate for all of the machining cutting-force frequency regimes in this research due to relatively low spindle speeds. The solid ball-end milling cutting tools of 8 mm diameter with two cutting edges, of 29.9° helix angle and 2.28° rake angle were used. The ball-end mills were made of a sintered tungsten carbide material K88UF with the hardness of 1770 HV. The cutting edges were coated with PVD-TiAlN coating.

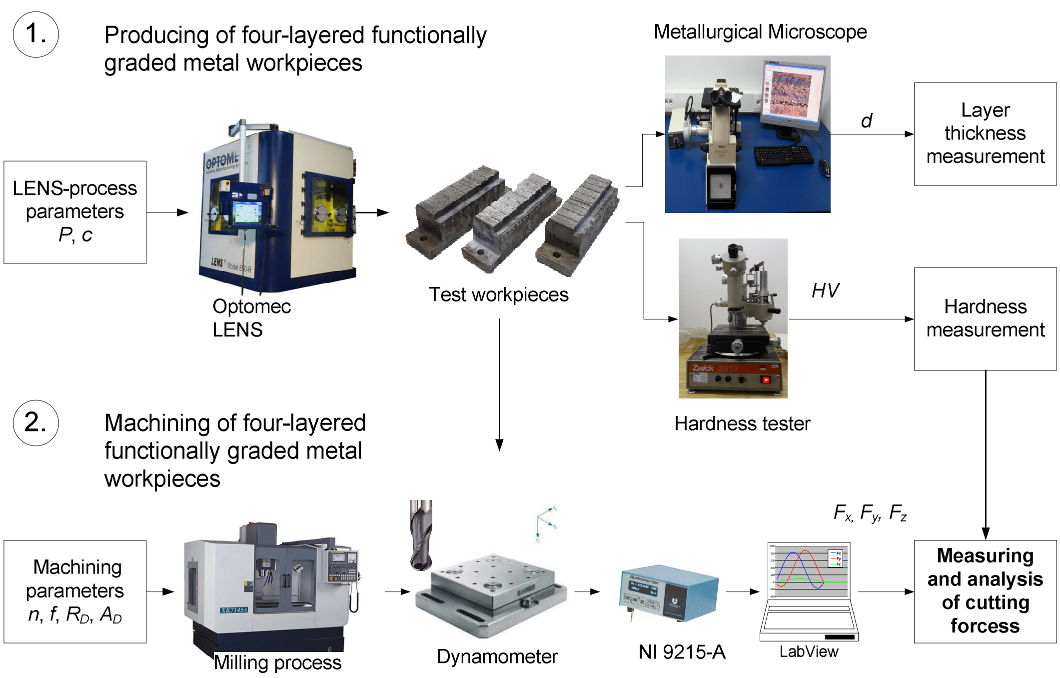

Fig. 1. Experimental scheme.

Table 2

Extract of machining experimental plan for LENS test no. 6

No.	*n* [min^{-1}]	*f* [mm/min]	A_D [mm]	Θ [°]	F_x [N]	F_y [N]	F_z [N]	No.	*n* [min^{-1}]	*f* [mm/min]	A_D [mm]	Θ [°]	F_x [N]	F_y [N]	F_z [N]
406	3000	200	0.5	25	181.9	179.4	-59.9	448	4000	250	1	25	106.7	129	-43.4
407	3000	200	0.5	50	195.6	195	-65.8	449	4000	250	1	50	99.2	117.8	-39.1
408	3000	200	0.5	75	7	11.2	5.8	450	4000	250	1	75	6.8	12.2	-7.6
409	3600	200	0.5	25	89.3	104.2	-34.7	451	3000	300	1	25	190.3	205.1	-68.6
410	3600	200	0.5	50	96	112.6	-38.2	452	3000	300	1	50	177	184.5	-63.8
411	3600	200	0.5	75	7.2	11.8	6	453	3000	300	1	75	7.2	10.6	-4.4
412	4000	200	0.5	25	38.8	59.2	-20.1	454	3600	300	1	25	151.2	158.4	-53.5
413	4000	200	0.5	50	32.9	66.32	-21.7	455	3600	300	1	50	139.1	146.9	-48.7
414	4000	200	0.5	75	6.4	11.4	-7.6	456	3600	300	1	75	4.8	10.6	-7.2
415	3000	250	0.5	25	193.1	186.6	-61.8	457	4000	300	1	25	102.0	151.8	-49.6
416	3000	250	0.5	50	207.6	204.9	-68.7	458	4000	300	1	50	81.1	147.8	-51.1
417	3000	250	0.5	75	5.6	12.3	-6.4	459	4000	300	1	75	-3.9	12.9	-4.8
418	3600	250	0.5	25	105.8	119.6	40.1	460	3000	200	1.5	25	208.6	200.7	-86.3
419	3600	250	0.5	50	117.6	130.1	-43.6	561	3000	200	1.5	50	229.2	223	-75
420	3600	250	0.5	75	4.8	11.0	-6.4	462	3000	200	1.5	75	4.4	12.6	-5.6
421	4000	250	0.5	25	78.9	101.2	-33.8	463	3600	200	1.5	25	114.1	132.9	-44.6
422	4000	250	0.5	50	85.8	110.3	-37.5	464	3600	200	1.5	50	125.4	146.9	-49.5
423	4000	250	0.5	75	7.2	9.8	-4.4	465	3600	200	1.5	75	5.2	12.2	-4.4
424	3000	300	0.5	25	203.1	196.2	-65.8	466	4000	200	1.5	25	110.4	122.8	-40.5
425	3000	300	0.5	50	223.2	218.1	-73.1	467	4000	200	1.5	50	120.3	132.9	-44.0
426	3000	300	0.5	75	6.4	13.9	-9.2	468	4000	200	1.5	75	6.4	9.4	-7.6
427	3600	300	0.5	25	121.2	133.0	-44	469	3000	250	1.5	25	233.7	223.9	-75.5
428	3600	300	0.5	50	133.2	134.4	-48.4	470	3000	250	1.5	50	256.8	246.1	-82.1
429	3600	300	0.5	75	4.8	12.2	-5.2	471	3000	250	1.5	75	7.2	10.2	-6.0
430	4000	300	0.5	25	88.8	130.6	-42.2	472	3600	250	1.5	25	148.4	148.5	-50.7
431	4000	300	0.5	50	99.1	138.6	-47.3	473	3600	250	1.5	50	159.6	165	-55.1
432	4000	300	0.5	75	7.2	-3.6	-2.4	474	3600	250	1.5	75	4.4	11.8	-5.6
433	3000	200	1	25	206.4	204.1	-68.6	475	4000	250	1.5	25	113.2	129.2	-43.7
434	3000	200	1	50	189.9	187.7	-63.8	476	4000	250	1.5	50	121.0	142.6	-48.1
435	3000	200	1	75	6.0	9.8	-6.9	477	4000	250	1.5	75	6.0	12.2	-6.4
436	3600	200	1	25	110.2	132.6	-45	478	3000	300	1.5	25	217.6	211.1	-69.5
437	3600	200	1	50	101.2	118.8	-41.7	479	3000	300	1.5	50	234.1	227.3	-76.4
438	3600	200	1	75	7.6	10.6	-6.8	480	3000	300	1.5	75	6.6	11.2	-5.3
439	4000	200	1	25	100.1	123.8	-41.2	481	3600	300	1.5	25	146.3	159.3	-54.1
440	4000	200	1	50	90.1	114.4	-37.1	482	3600	300	1.5	50	157.3	175.9	-58.8
441	4000	200	1	75	5.6	12.2	-7.6	483	3600	300	1.5	75	6.0	10.6	-6.4
442	3000	250	1	25	247.2	238	-79.9	484	4000	300	1.5	25	133.0	145.8	-50.2
443	3000	250	1	50	225.6	219.0	-73.5	485	4000	300	1.5	50	143.0	162.74	-54.6
444	3000	250	1	75	5.2	11.8	-4.8	486	4000	300	1.5	75	5.6	12.6	-6.4
445	3600	250	1	25	145.2	153.1	-51.0	LENS test no. 6 (*P* = 380 W, *c* = 60 mm/s); Cutting tests no. 136 to 162							
446	3600	250	1	50	130.7	140.8	-47.0								
447	3600	250	1	75	6.8	9.4	-7.6								

The machining tests were carried out for all combinations of machining parameters and LENS process parameters. One and/or three values for the radial and axial depth of cut have been selected: R_{D1} = 0.2 mm; A_{D1} = 0.5 mm, A_{D2} = 1 mm, A_{D3} = 1.5 mm. The following values for spindle speed and feed rate have been selected: n_1 = 3000 min^{-1}, n_2 = 3600 min^{-1}, n_3 = 4000 min^{-1}; f_1 = 200 mm/min, f_2 = 250 mm/min, f_3 = 300 mm/min. The combination of three values for the Laser power (*P*) and the cladding speed (*c*) was used to make the four-layered material: P_1 = 300 W, P_2 = 380 W, P_3 = 400 W; c_1 = 30 mm/s, c_2 = 48 mm/s, c_3 = 60 mm/s.

The workpiece material is made of a 16MnCr5 basic material and 4 stainless steel. Nine such belts of stainless steel layers were cladded on a singular workpiece with the 60 mm thickness, length of 180 mm and width of 70 mm. By varying the two LENS process parameters, 9 different test workpieces (9 tests) of four-layered metal material with different layer hardness and thickness were produced on the Optomec LENS 850-R machine.

The overlapping in all layers was set to 40 %. The diameter of laser ray was 0.8 mm. The experimental setup can be seen in Fig. 1.

The Vickers hardness of manufactured layers was measured by 7061 Zwick 3212 hardness tester. Layer thicknesses d of the manufactured metal material were measured with a Nikon Epiphot 300 Inverted Metallurgical Microscope.

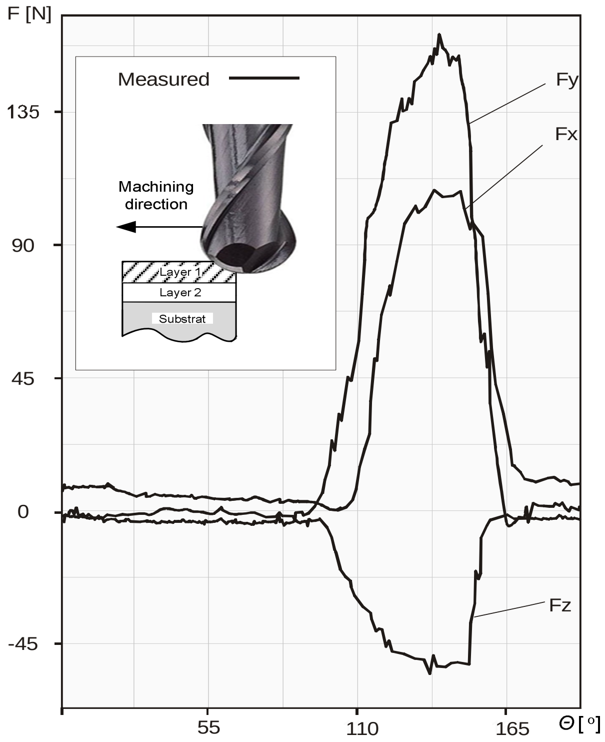

Fig. 2. Course of measured cutting forces for 16MnCr5 / 316L four-layered functional graded metal material at middle depth of cutting; A_D = 0.55d; (test no. 144).

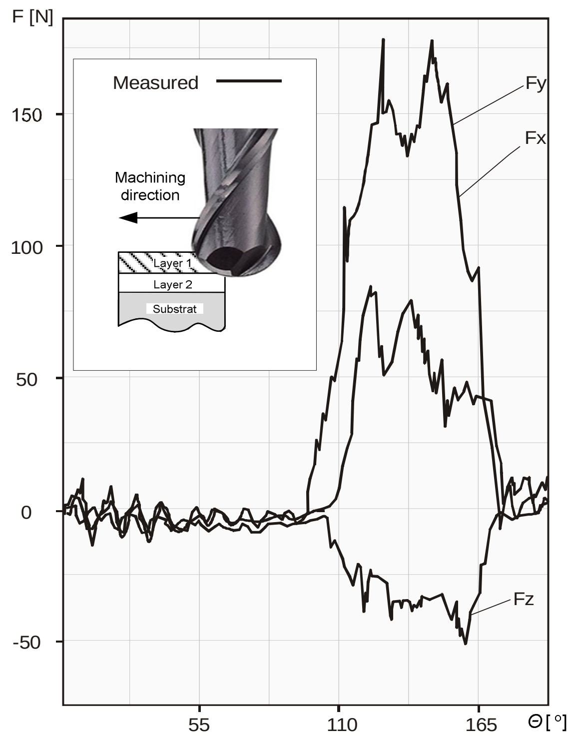

Fig. 3. Course of measured cutting forces for 16MnCr5 / 316L four-layered functional graded metal material at high depth of cutting; $A_D \approx d$; (test no. 163).

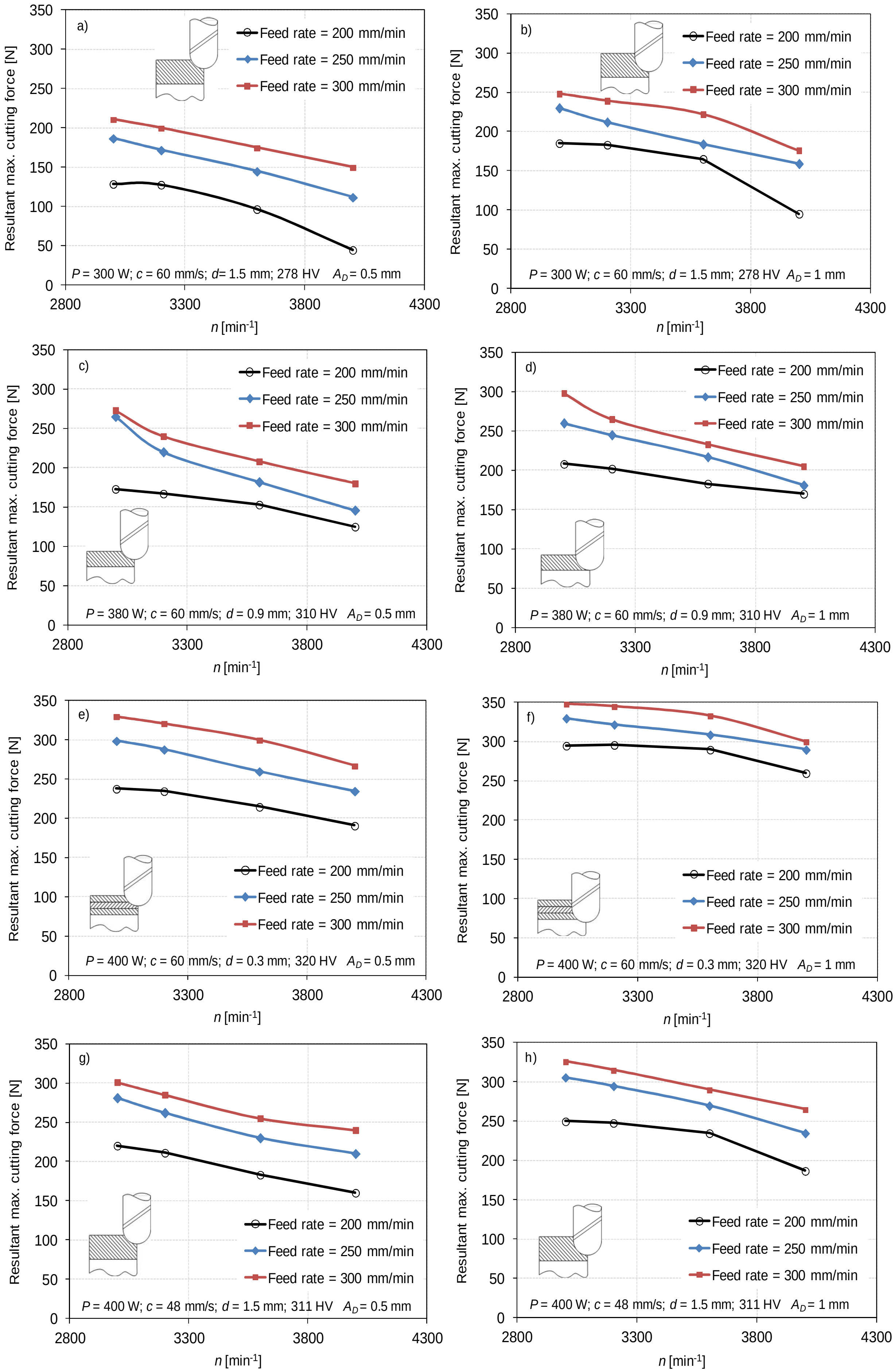

Fig. 4. The influence of LENS process parameters and cutting conditions to the magnitude of the resultant maximal cutting force.

3. ANALYSIS OF CUTTING FORCES

The measured cutting forces are graphically represented by diagrams depending on the angle of rotation of the cutting tool (Figs. 2 and 3). Samples of the cutting forces obtained during milling of the four-layered metal material are represented by a continuous line. The force signals outline the tool engagement in 1/2 revolution. Each force signal was obtained by averaging ten one-revolution engagements at different time periods in the cutting test in order to eliminate signal anomalies due to the inhomogeneity of the manufactured stainless steel layers. The force signals clearly outline one characteristic peak corresponding to the engagement of the one flute, separated by periods of no engagement. The rise of the cutting forces in each cycle is due to the increase of chip thickness from zero at the cutting edge entry to a maximum at the exit. The force signal is also influenced by the direction of layer cladding. The order in which the peak forces appear and the spacing between them is also related to the number of manufactured layers and their thickness.

The cutting forces at the ratio A_D / d = 0.55 are relatively higher than expected for milling at the ratio $A_D \approx d$ (Figs. 2 and 3). The signals of cutting forces have more oscillations probably due to the material inhomogeneity at the boundary between separate deposited steel layers. The chip obtained in this boundary is very small and heavily discontinuous. Force oscillations and magnitude increase slightly when A_D becomes larger than d.

Plots have been made to determine the variation of LENS and machining parameters to the course of the resultant cutting force. A small part of these plots were outlined in Fig. 4.

Plots on Fig. 4 show that the cutting force decreases when the spindle speed increases at the constant feed rate and depth of cut.

The relationship is close to a linear trend. From plots it is evident that feed rate has the largest impact on cutting force.

The cutting force decreases when the feed rate decreases.

It is also evident that the force signal for the multi-layered material is characteristic of the architecture of the material, which depends on the LENS machine settings.

Figures 4a to 4f demonstrate that the cutting force increases significantly (up to 60 %) when the P setting increases from 300 W to 400 W at the constant c (60 mm/s) and constant machining parameters.

Figues 4e and 4g indicate that F increases moderately (for 16%) when c increases from 48 mm/s to 60 mm/s at constant P (400 W) and A_D. The analysis of the plots indicates that two-way (dual) effect interaction $P \times c$ has a significant effect on the value of the resultant cutting force F. It could be observed from plots on Fig. 4 that the laser power setting has the second largest impact on the cutting force.

Figures 4b, 4d, and 4f demonstrate that the cutting force increases significantly (by 40%) when the manufactured layer thickness decreases (1.5 mm down to 0.3 mm) at the same cutting parameters.

By comparing Figs. 4f and 4g, it is found that when cutting with constant A_D = 1 mm at the ratio A_D/d = 3.3, the cutting forces are 8% higher in comparison to cutting at the ratio A_D/d = 0.6.

Therefore, the cutting forces are higher when the cutting involves more than one layer.

4. CONCLUSIONS

This paper presents the results of experimental investigation of cutting forces during end-milling of four-layered functionally graded metal material.

Based on the experimental data analysis were preformed in order to obtain the correlation between resultant maximal cutting force, cutting conditions and LENS process parameters. Hardness and thickness of the particular deposited layer in multi-layered metal material has been considered in the analysis.

An effort is made to include all significant machining/process parameters that influence the cutting forces.

The following conclusions can be drawn from the results of performed analysis:

- Laser power and cladding speed have the largest impact on the hardness and thickness of the manufactured layer in the four-layered metal material.
- The deposited layer thickness has a significant influence on predicted cutting forces.
- The cutting forces when milling at the middle depth of cutting (A_D / d = 0.55) are relatively higher than expected for milling when the $A_D \approx d$. Force signals also exhibit more oscillations. This is probably due to the material inhomogeneity at the border between separate stainless steel layers. The chip obtained in this region is very small and heavily discontinuous. Force oscillations and magnitude increase slightly as A_D becomes larger than d.

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