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Surface integrity analysis of duplex steel by design of experiment approach

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Abstract

Separation of solids and liquids from water is an actual problem in the water waste, chemical, oil, and food processing industries. The purpose of water treatment facilities is to purify water which contains minimal amounts of solids and liquids and at the same time this technology should allow to process large amounts of water and be energy-efficient. That is why a new type of counter flow decanter centrifuge was constructed and appropriate experiments on prototype production were carried out to optimize machining parameters. Output data were analyzed by statistical methods. As a result of these experiments statistically significant factors that affect surface integrity were determined.

Keywords: counterflow decanter centrifuge; design of experiments; surface integrity; water treatement

1. Introduction

Duplex steels are among the hard-to-machine materials and during the machining they are generally prone to mechanical strengthening, which alters the mechanical properties of the surface layer. Mechanical strengthening when turning may ultimately lead to heterogeneous surface during machining. The heterogeneous manifestations include creating an unstable chip and vibration. These vibrations together with the high cutting forces and high temperatures are responsible not only for large machine tools wear and shortened life span, but also for the

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formation of structural in homogeneities on the new surface [1]. They are most frequently observed local inhomogeneity of macroscopic and microscopic residual stresses, possibly caused by changes in phase structure due to high temperatures common in turning, and lower thermal conductivity of the duplex steels [2]. This article deals with the analysis of surface integrity parameters, specifically the residual stress (σA a σT), the degree of plastic deformation (W_A and W_T) and the surface roughness parameters (Ra, Rz, R_{SM}) in dependence on cutting parameters when turning.

2. Samples and experimental design

Sample DRUM – CONE, part of decanter centrifuge used for dewatering of industrial sludge, was made of Cr-Ni-Mo-N austenitic-ferrite stainless steel castings (1.4470; GX2CrNiMoN22, 5-3) in the production capacities of První brněnská strojírna Velká Bíteš, a.s. The surface of the drum is machined by turning as final technology. There were two kinds of drums diameters 205 and 235 mm, number of revolutions per minute when machining was selected to 70, respectively 90. Depth of cut (a_p) was constant and was equal to 0.2 mm.

The purpose of the experiment was to study the influence of factors that included *cutting speed (A)* and *feed rate (B)* for the following parameters: *the residual stress (σ_A a σ_T), the degree of plastic deformation (W_A and W_T) and the surface roughness (Ra, Rz, R_{SM})*. Factors were set to the following levels:

- *cutting speed (A)* - 45, 65 m / min.;
- *feed rate (B)* - 0.1, 0.2, 0.3 mm / rev.

A full factorial design with two replications was used, i.e. there were 12 runs of the experiment. Order of machining of samples is shown on figure 1. Design and analysis were performed in the software Design-Expert 6 ® and Minitab® Statistical Software.

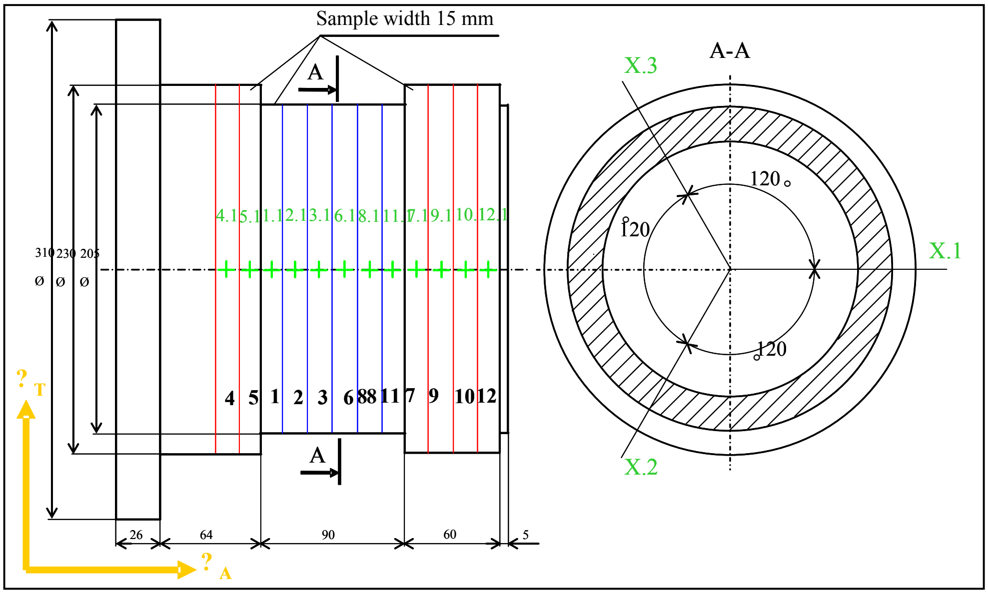

Fig.1. Simplified schematic view of production order (turning) of individual samples and analyzed network representation of the selected points marked with lines of residual stress determination.

3. Theory of analysis

To investigate effects of factors screening analysis was carried out that uses linear models to detect influences in general. There were 4 possible models in conducted experiment. In preference to investigate effects two-way complete model (1) was used, it contents effects of factors and interaction effect. If absence of interaction is obvious two-way main-effects model can be used (2). In exceptional case one-way models for effect A or B (3, 4) were used.

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \quad (1)$$

$$y_{ijk} = \mu + \tau_i + \beta_j + \varepsilon_{ijk} \quad (2)$$

$$y_{ik} = \mu + \tau_i + \varepsilon_{ik} \quad (3)$$

$$y_{jk} = \mu + \beta_j + \varepsilon_{jk} \quad (4)$$

where τ_ι – effect of factor *cutting speed (A)*, β_φ – effect of factor *feed rate (B)*, $(\tau\beta)_{ij}$ – effect of factors interaction, ε_{ij} - independent random errors with $N(0, \sigma^2)$. So, it is necessary to test following hypothesizes: H0: $\tau_i = 0$, i = 1, 2, 3 (factor A is not significant), H0: $\beta_j = 0$, j = 1, 2 (factor B is not significant), H0: $(\tau\beta)_{ij} = 0$, i= 1, 2, 3; j = 1, 2 (interaction is not significant) [3].

For hypothesizes testing Analysis of Variance (ANOVA) was carried out; it gives possibility to compare several averages at the same time. In ANOVA the F-test is used for comparisons of the components of the total deviation. F-statistic (5) compares to F-distribution with corresponding degrees of freedom.

$$F = \frac{\text{variance between groups}}{\text{variance within groups}} \quad (5)$$

The null hypothesis, that factor or interaction has no effect, is rejected if the F-statistic calculated from the data is greater than the critical value of the F-distribution for type I error probability. For compare result F-statistic to desired type I error probability takes advantage p-value. p-value is the probability, assuming the null hypothesis is true, of observing a result at least as extreme as the test statistic. So, if p-value is less than or equal to significant level of type I error, then the null hypothesis is rejected at the given level of significance. That means one factor in a model or observed factor has significant influence on response value [4].
In this study significant level of type I error is 0.05.

If the model is significant by ANOVA and one or more factors were significant it is necessary to check model assumptions. Following checks were used [5].

- Check the form of the model.
- Check for outliers.
- Check for independence of residuals.
- Check for constant variable.
- Check for normality of residuals.

4. Results and discussion

4.1. Residual stress (σA a σT) and, the degree of plastic deformation

Diffraction strain gauge measurements were conducted to investigate the effect of factors A and B on residual stress. Radiographic analysis of strain gauge was conducted on the surfaces of all twelve samples labeled 1 to 12. On each sample was selected 3-digit level of 120 °, see fig. 1. The analyzed points were measured in both of the tool feed direction δ_A, and that is the direction perpendicular δ_T.

The measurement was carried out using ψ goniometer Xstress 3000 G2, X-ray tube with chromium anode and a cylindrical collimator with a diameter of 3 mm. The irradiated region area was about 9 mm^2. Diffraction line {211} α-Fe was analyzed. Residual stress values were calculated from the lattice deformation of the experimental set dependencies 2θ (sin ² ψ) provided dual axis state of residual stress (θ is the diffraction angle, ψ - the angle between sample surface and the diffracting lattice planes). Depending $2\theta^{211}$ (sin ² ψ) were measured in two azimuth σ_A and σ_T (Fig. 1). Diffraction angle $2\theta^{211}$ autocorrelation method was determined from duplicate CrKα diffracted at the lattice planes {211} α-Fe. When calculating the voltage was applied macroscopic Young's modulus of 2.1 GPa and Poisson's ratio 0.3. Experimental error, see the individual values measured by standard deviation of residual stress calculation algorithm using the "sin ² ψ" [http://www.stresstechgroup.com/].

Quantities W_A, W_T is the average integral width of diffraction line {211} α-Fe measured by σ_A and σ_T, and represent the degree of plastic deformation of samples analyzed in these directions.

Table 1. Levels of design factors and individual values of residual stress and plastic deformation.

Run	Factor A Cutting speed V_c, *m/min*	Factor B Feed rate f, *mm/rev*	$\langle\sigma_A\rangle$, MPa	$\langle W_A\rangle$, deg	$\langle\sigma_T\rangle$, MPa	$\langle W_T\rangle$, deg
1	*45*	*0,3*	667	3,13	546	3,18
2	*45*	*0,1*	222	3,27	481	3,06
3	*45*	*0,1*	127	3,09	557	3,08
4	*65*	*0,2*	288	3,26	600	3,06
5	*65*	*0,1*	-209	3,26	121	3,09
6	*45*	*0,2*	352	3,28	599	3,18
7	*65*	*0,2*	233	3,31	633	3,22
8	*45*	*0,2*	434	3,23	582	3,16
9	65	0,3	561	3,31	558	3,27
10	*65*	*0,1*	313	3,03	593	3,02
11	*45*	*0,3*	536	3,54	422	3,46
12	65	0,3	423	3,43	709	3,25

Table 1 contains the design factors and the corresponding responses of the residual stress and degree of plastic deformation there were measured in two directions (axial and tangential).

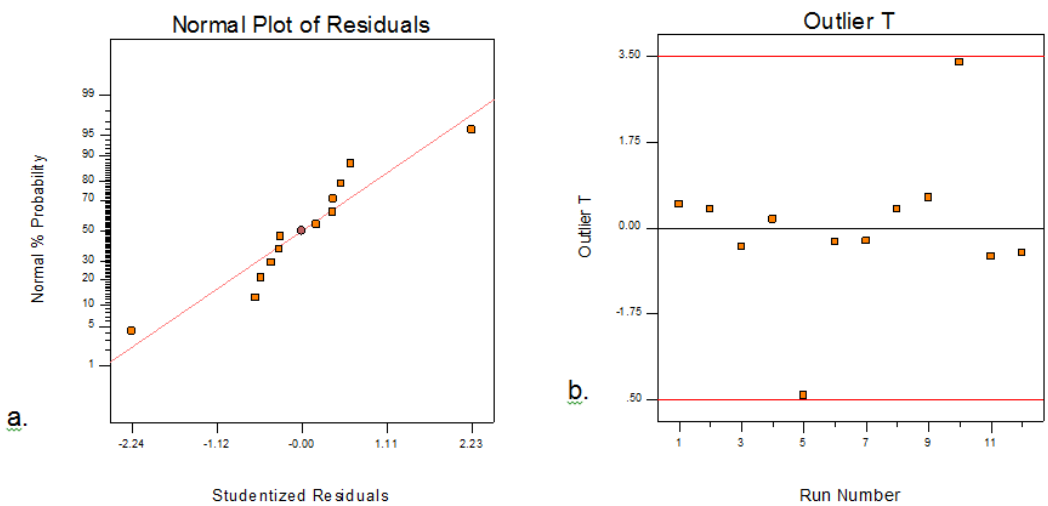

Fig. 2. Interaction graph of residuals axial direction.

In the ANOVA results for residual stress axial direction the two-way complete model was not significant with p-value = 0.1016. From figure 2 it is possible to observe no interaction effect, because lines on graph are parallel. It is confirmed by p-value for interaction in ANOVA table that equals to 0.9951. So, two-way main-effects model was tested and it was indicated p-value = 0.0135, the two-way main-effects model demonstrates dependence residual stress σA on the factor B as well. Normal probability plot on the figure 3a shows that residuals have non-normal distribution; it means the model can't be significant. The reasons of this distribution are two points there are location too away from the middle line, as shown at figure 3b; the factor A and the factor B set to 0.1 mm/rev and 65 m/min, respectively. This fact is caused by a change in cutting conditions, where just at the highest ratio f / vc speed (f = 0.1 mm / rev. To vc = 65 m / min) leads to redistribution of cutting force and thus change the nature of residual stresses.

Response analysis of residual stress in tangential direction showed no dependence on the factors. Again, large variability found when factors A and B were set to 0.1 mm/rev and 65 m/min, respectively. As mentioned above this is due to the high ratio of f / vc (f = 0.1 mm / rev. To vc = 65 m / min), which leads to redistribution of cutting force and thus change the nature of residual stresses.

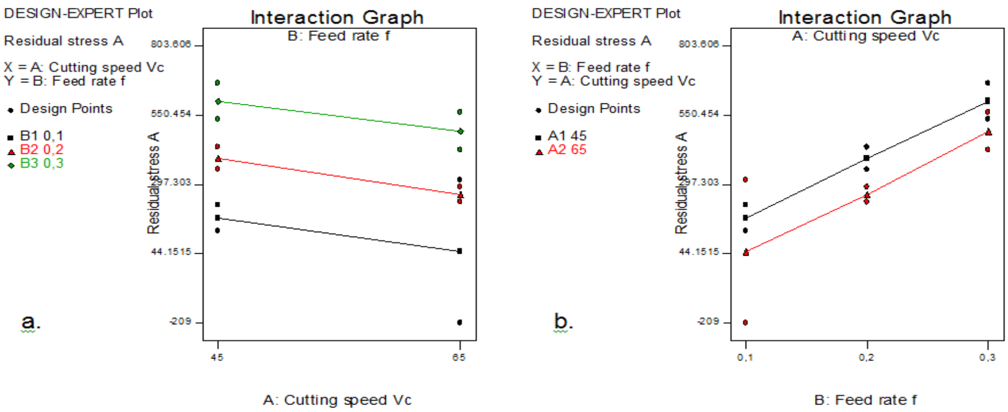

Fig. 3. a) Normal probability plot of residuals of residual stress axial direction, b) Outlier T test for residuals of residual stress axial direction.

In studying the degree of plastic deformation in axial direction two-way complete model was chosen, but the ANOVA showed the absence of significant dependence by the p-value that was equal to 0.6625. So factor couldn't be statistic significant. Models (2), (3) and (4) were tested as well and were rejected at confidence level 0.05 too. Thus although the mean value increases when feed rate increases (more fig 4.), factor feed rate cannot be accepted as statistical significant. That is mainly by reason of large variability where factors A and B were set to 0.3 mm/rev and 65 m/min, in other case most likely model and effect of factor A would be significant.

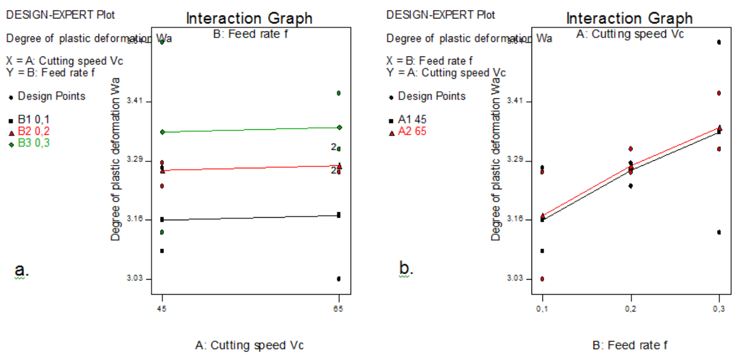

Fig. 4. Interaction graphs for degree of deformation in axial direction.

Analysis of the degree of plastic deformation in tangential direction by two-way complete model also showed that the model must be rejected, because p-value for this model was 0.1599. But for the model without interaction p-value does not exceed the limit of 0.05, which means that this model cannot be refused. In other tests also was not found a reason for rejecting the model. Based on the p-value for the factor B equal to 0.0148 it is possible to judge the significance effect of this factor even though the variation remained where factor A and B were set to levels 0.3 mm/rev and 65 m/min. The trend of increasing degree of plastic deformation is shown on figure 5.

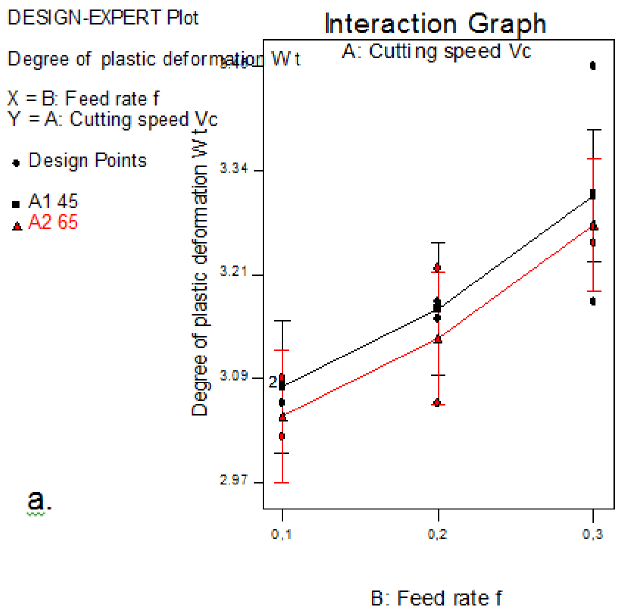

Fig. 5. Individual Values of degree of deformation in tangential direction.

Measured results shows that higher feed rates lead to higher edge load (this effect is caused by rapid strengthening of austenitic steels), producing higher tensile residual stresses and analysis of the diffraction profile shows a higher degree of plastic deformation.

4.2. Surface roughness

Surface roughness was measured by the Mahr XCR 20 profile meter using PGK units and sensor MFW-250 # 1805 [4.7%]. The measurement results are shown in Table 2. Roughness profile of the part was described by parameters: Ra, Rz, RSm.

For the parameters of surface roughness two-way complete model was chosen first, it was significant by ANOVA. But residuals had a not-normal distribution (fig. 6a) and two outliers were observed (fig. 6b). However, it is obvious relations between responses and factors (fig. 7). With increasing cutting speed or feed rate the surface roughness parameter Ra increases. As shown on figure 7. Dependence of factor A is more powerful when factor B is set on level 0.2 or 0.3mm/rev and lines are not parallel, it indicates existence of interaction between cutting speed and feed rate. Table of ANOVA confirms the assumption of interaction, but results cannot be statistical accepted because of non-normal distribution. In case data do not have normal distribution it is appropriate to use ranking transformation (for example Kruskal-Wallis's test or Friedman's test), but these tests do not support analysis of interactions. So a Tukey's method for multiply comparisons was carried out.

Table 2. Measured values of surface roughness parameters Ra, Rz, RSm.

Run	Factor A *m/min*	Factor B v_c *mm/rev*	Surface roughness Ra	Surface roughness Rz	Surface roughness RSm
1	45	0,3	1,68	6,919	311,798
2	45	0,1	0,485	2,776	140,705
3	45	0,1	0,457	2,571	170,46
4	65	0,2	1,88	7,614	210,752
5	65	0,1	0,747	3,561	112,197
6	45	0,2	1,025	4,062	210,525
7	65	0,2	2,151	7,384	211,083
8	45	0,2	1,007	4,203	215,052
9	65	0,3	2,805	11,206	316,069
10	65	0,1	0,602	2,848	104,472
11	45	0,3	1,69	6,983	316,078
12	65	0,3	2,799	10,984	316,388

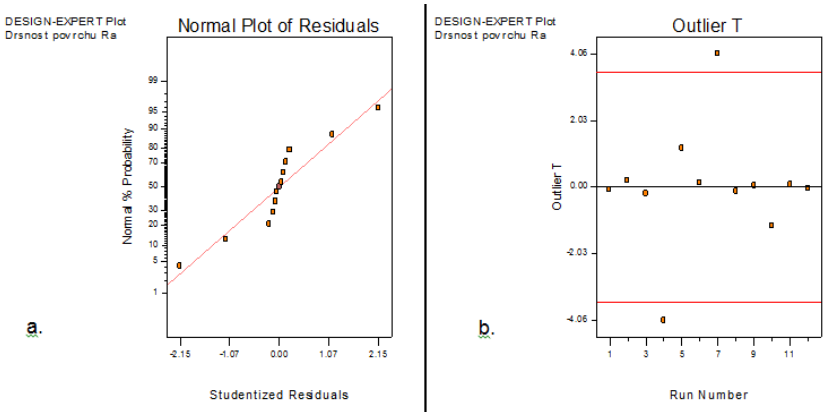

Fig. 6. Model tests for Ra parameter: a) Normal probability plot of residuals, b) Outlier test.

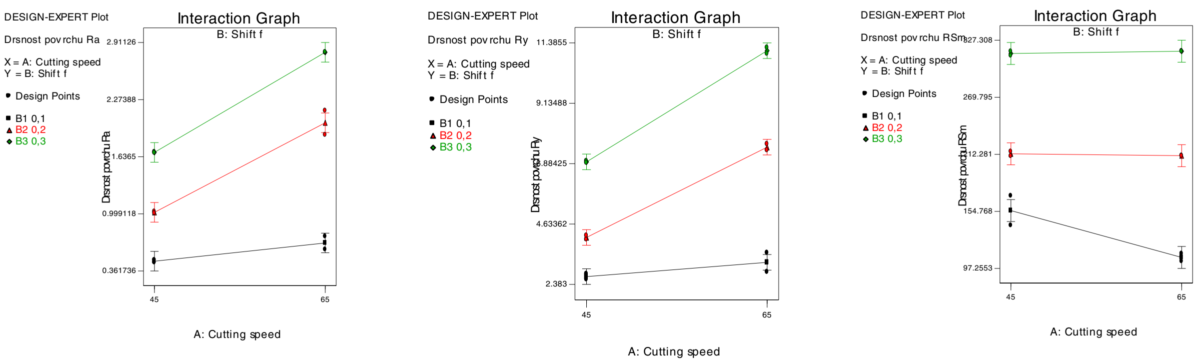

Fig. 7. Interaction graph of parameters Ra, Rz and Rsm.

The case of Rz is very similar to Ra. There is obviously correlation between Rz and factors (but two-way complete model for response Rz was not significant by Normal test for residuals and Outliers test. Further analysis was conducted in the same way as Ra. Surface roughness parameter Rsm shows no strong effect on factor A (cutting speed) except on level 0.1mm/rev of factor B.

5. Conclusion

In the present work, the analysis of experiments has been developed to evaluate effect of manufacturing factors cutting speed (Factor A) and feed rate (Factor B) of the cutting tool on selected surface integrity parameters: the residual stress and the degree of plastic deformation and surface roughness when machining austenitic-ferrite stainless steel GX2CrNiMoN22. In cases of residual stress parameters original data had a large variability. This has to be respected when formulating conclusions.

Feed rate affects residual stress axial direction and degree of plastic deformation. On residual stress in tangential direction and degree of plastic deformation any factor has no statistically significant effect. Both factors have statistically significant effect on surface roughness parameters Ra, Rz where increase of factors affect increased surface roughness. But when feed rate is set to level 0.1mm/rev factor cutting speed has smaller effect. Regarding parameter Rsm, the feed rate affects Rsm the same way, but cutting speed has reverse influence when feed rate is set to 0.1mm/rev and no influence when feed rate is set to 0.2 or 0.3 mm/rev.

Results that we have obtained from this research were used to optimize cutting parameters for the selected machining parts of decanter. Next step in our research will be optimization of operating parameters of assembled decanter centrifuge in order to achieve the highest percentage of solids using statistical methods.

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