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Original Research

Effect of Floating-Plug Drawing Process Parameters on Surface Finish of Inner and Outer Surfaces of AISI 321 Stainless Steel Thin-Walled Tubes

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Abstract

This article presents the results of the analysis of changes in the surface topography of AISI 321 (1.4541) thin-walled stainless steel tubes in single-pass Floating-Plug Drawing (FPD) process. Experimental tests were carried out with variable drawing speed (1, 2, 3, 4, 6, and 10 m/min) and different angles of floating plug (11.3°, 13° and 14°). Wisura DSO7010 (Fuchs Oil) lubricant was used in the experiments. Mean roughness Ra and ten point height of irregularities Rz were adopted as surface quality indicators. Roughness parameters were measured independently on the inner and outer surfaces of thin-walled tubes. Analysis of variance was used to analyse the relationship between process parameters (drawing speed and angle of floating plug) and surface roughness of tubes. A decrease in the values of both analyzed roughness parameters was observed as a result of the drawing process. The FPD process significantly improves the inner surface quality of AISI 321 thin-walled stainless steel tubes. The mean roughness value tends to increase with increasing drawing speed, while the angle of the floating-plug has no significant effect on the mean roughness Ra.

Keywords: analysis of variance, floating plug, stainless steel, surface roughness, tube drawing

1. Introduction

Floating-plug drawing (FPD) process has become the most advanced technology in the manufacture of thin-walled seamless tubes. The main advantages of FPD process are high wall thickness reduction ratio, high productivity and thin walls (Pernis & Kasala, 2013). A floating plug does not limit the length of a manufactured tube (Pernis, 2001). The undoubted limitations of drawing technology are the small production possibilities related to the characteristics of the process in terms of the shape of the manufactured products. In the tube drawing process, unlike rod drawing, the external and internal surfaces of the pipe are formed simultaneously. Thick-walled tubes can be drawn using floating-plug drawing process only under the condition that plug head diameter is smaller than diameter of the die (Pernis & Kasala, 2013). Moreover, through appropriate heat treatment of metal before the drawing process, it is possible to obtain high-strength products while maintaining good plastic properties (Bartnicki & Pater, 2005; Łuksza, 2001).

Drawing technology includes the processes of preparing material for drawing and the finishing processes of drawn products. If the surface of the workpiece is covered with a layer of oxides, it should be removed by etching in acid solutions. The phenomenon of friction in drawing processes is unfavorable and causes uneven deformation and increases the drawing force (Necpal et al., 2018). It is estimated that approximately 30-50% of the total drawing force is used to overcome friction forces (Skoblik & Wilczewski, 2006). Uneven deformations cause local residual stresses and create material defects (Martínez et al., 2022). Excessive friction causes rapid wear of dies and makes it difficult to obtain the appropriate smoothness of the surface of the finished products (Patil et al., 2020; 2021). To reduce friction, metallic, phosphate or lubricant coatings can be applied to the surface of the workpiece immediately before processing. Reducing friction is achieved by using appropriate liquid lubricants which are a composition of various oils or solid lubricants (de Castro Maciel et al., 2016; Larsson et al., 2019). In drawing components from high-strength steels and alloys, the so-called self-lubricating coatings facilitating the forming process. To ensure liquid friction conditions, hydrostatic and hydrodynamic lubricant feeding methods are used (Byon et al., 2011).

Optimisation of the floating-plug drawing process of difficult-to-form materials was presented by Pasierb et al. (2000). The developed computer program allowed for the determination of optimal technological parameters of the drawing process of materials that are difficult to deform. In another article, Żaba and Pasierb (2004) investigated the influence of the geometry of dies and plugs as well as the drawing speed on the properties of 1H18N10T steel tubes drawn using floating plug. The investigations were focused on the analysis of microhardness on the cross-section of tubes before and after drawing. Pernis and Kasala (2013) investigated the conditions under which tube drawing of thick-wall tubes is possible. They also provided equation that enables to calculate the difference of die and plug angles to achieve stable drawing conditions. Campos and Cetlin (1998) investigated the effect of the coefficient of friction (CoF) on the decrease of uniform tensile elongation of copper bars. They found that CoF has no influence on the elongation. Świątkowski and Hatalak (2001) proposed a floating plug to stabilise of the tube drawing process. The proposed tool increases the wall-thickness reduction ratio and provides the minimization of the zone of tube sinking. Smith and Bramley (1973) for the first time used the upper-bound technique to establish the relative importance of the various parameters of the FPD proces.

The tube drawing process has been analyzed using various numerical methods e.g. finite element method (Kwan, 2002; Yoshida et al., 2001) and upper bound method (Pouyafar et al., 2022). Danckert and Endelt (2009) conducted FE-based numerical modelling of FPD and proposed a new plug design with "self-catching plug" principle, where the cylindrical plug land is replaced with a circular profiled plug land (conventionally the plug land is cylindrical). The self-catching plug reduces the risk for failure during start up of the FPD process. Wang and Wang (2008) modified conventional slab model (CSM) to analysed FPD process of hollow copper tubes. They concluded that proposed model was more accurate than the CSM. Um and Lee (1997) found that the drawing stress in the tube drawing with a fixed plug is related to the increase in the CoF. Rubio et al. (2006) modelled the plastic deformation zone using triangular rigid zones which allowed to calculate the dimensional overall energy involved in FPD process. Shen et al. (2009) investigated the effect of equivalent strain, equivalent stress and temperature on the stability of the FPD process of copper tubes with pores. The analyses were carried out using finite element software Msc.Marc. It was found that the floating-plug axial movement affect the surface finish of the tube with pores. Rubio et al. (2017) provided the guidelines for selecting plugs used in the FPD of thin-walled tubes. The theoretical considerations on the floating plug positions in the deformation zone are given by Sadok and Pietrzyk (1981).

As shown by the review of literature, research works on designing of tube drawing process are focused on optimization of the plug shape, lubrication conditions and mechanical properties of the components. However, analysis of the surface finish of stainless steel thin-walled tubes has not attracted much attention. Therefore, this article presents the results of the analysis of surface topography changes of thin-walled AISI 321 stainless steel tubes in FPD process. Analysis of variance was used to analyse the relationships between process parameters (drawing speed and angle of floating plug) and tube surface roughness parameters.

2. Material and methods

2.1. Test material

Experimental tests using the FPD process were carried out on austenitic chromium-nickel-stainless AISI 321 (EN symbol X6CrNiTi18-10) steel pipes. The outer diameter of the pipes was 19 mm and the wall thickness was 1.2 mm. In order to facilitate the drawing process, the outer surface of the tubes was grinded and etched. Grinding was intended to create oil pockets on the surface of workpiece, which ensures that the appropriate amount of oil is supplied to the contact zone. Proper lubrication is crucial in the FPD process. It reduces the non-uniformity of deformation and limits the generation of heat caused by friction.

2.2. Experimental procedure

Thin-walled tubes were drawn on a floating plug (Fig. 1) using a drawing machine with a maximum capacity of 70 kN. Floating plugs were made with a half angle of the angle of inclination of the conical part of the plug β = 11.3° (L = 22.8 mm), 13° (L = 22 mm), and 14° (L = 21.7 mm). A die was used with the following geometry D_k = 16, mm, α = 16° (Fig. 2). Both die and floating plug were made of a tungsten carbide G10. The tubes were drawn at speeds of 1, 2, 3, 4, 6, and 10 m/min. Wisura DSO7010 (Fuchs Oil) lubricant was used in the experiments. The geometric parameters of the tubes before and after drawing are listed in Table 1.

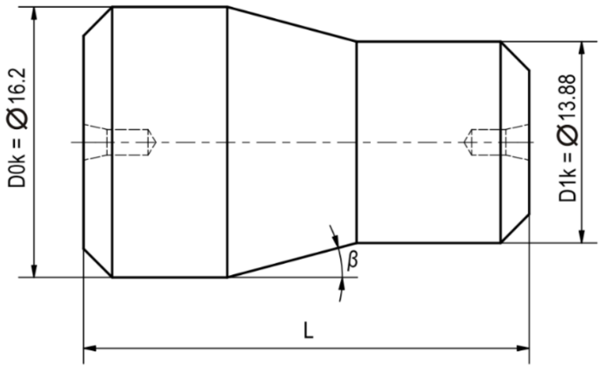

Fig. 1. Geometry of floating plug (dimensions in mm).

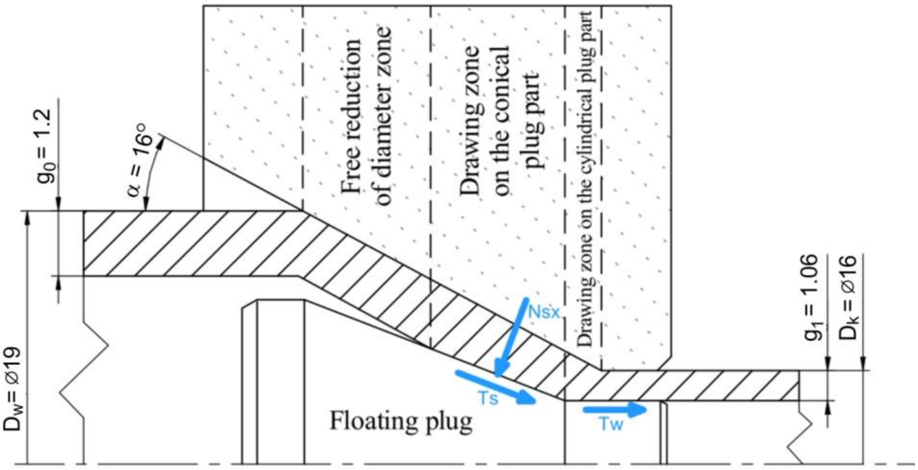

Fig. 2. Schematic diagram of the FPD process (dimensions in mm).

Table 1. The geometric parameters of the tubes before and after drawing.

Parameter	Value	
	before drawing	after drawing
Outer diameter	19 mm	16 mm
Wall thickness	1.2 mm	1.06 mm

The essence of the floating-plug drawing process is shown in Fig. 2, which shows a cross-section through the deformation zone. A floating plug is inserted into the pipe in front of the die, then the pipe is crimped. After inserting the workpiece into the die, the drawing process begins. The shape and dimensions of the plug are selected so that the frictional forces of drawing are equal to the pushing forces coming from the contact force N_{sx}. The pulling forces have two components: T_s – the friction force in the conical part of the plug, T_w – the friction force in the cylindrical part of the plug (Fig. 2). The balance condition of plug can therefore be written as (Nowosielski et al., 2014):

$$N_{sx} = T_s + T_w \tag{1}$$

The surface roughness of the inner and outer surfaces of the tubes were measured using LEXT OLS4100 confocal laser microscope with 405 nm UV laser light (Leica Microsystems). Surface roughness results are presented by the two most commonly used parameters, i.e., Ra – arithmetic average of the absolute values of the profile heights over the evaluation length and Rz – the average value of the absolute values of the heights of five highest-profile peaks and the depths of five deepest valleys within the evaluation length. The ground surface of the batch material and the surfaces of the tubes after drawing were analysed.

2.3. Analysis of variance

The experiment was designed to investigate the effects of three input factors: Drawing speed, angle of floating plug β and two surface roughness parameters (Ra and Rz) responses. The factor levels were coded to facilitate the analysis. The significance of the model and the model terms were determined using the F-value and the p-value. Model terms with *p*-values less than 0.05 were considered significant. Model terms with *p*-values greater than 0.05 were considered not significant. The models were evaluated based on the following parameters. Sequential *p*-value was used to determine the significance of the model. A smaller *p*-value generally indicates that the model is significant. Lack of fit *p*-value was used to check the goodness of fit of the model. A larger *p*-value is desirable as it indicates a satisfying fit. Adjusted R^2 is the coefficient of determination, adjusted based on the number of predictors in the model. It indicates the proportion of the variance in the dependent variable that is predictable from the independent variables. A higher adjusted R^2 indicates a better fit of the model. Predicted R^2 is an estimate of the population coefficient of determination. It provides an indication of how well the model will predict responses for new observations. A higher predicted R^2 indicates a better predictive ability of the model. The integrity of fit of the models was evaluated using several fit statistics including standard deviation, mean value, coefficient of variation, R^2, adjusted R^2, predicted R^2 and adequate precision. A predicted R^2 in reasonable agreement with the adjusted R^2 (i.e., the difference is less than 0.2) and an adequate precision ratio greater than 4 were considered desirable for navigating the design space.

Table 2 presents the data used in the analysis of variance. The angle of floating plug and drawing speed were used as input (explanatory) variables. Two independent analyzes of variance were performed. In the first analysis, the Ra parameter measured on the inner and outer surfaces of the tubes was used as the output (explained) variables. In the second model, the parameter Rz measured on the inner and outer surfaces of the tubes were used as output variables.

Table 2. Roughness parameters Ra and Rz of inner and outer surfaces of tubes.

Angle of floating plug β, °	Drawing speed v_c, m/min	Ra, μm		Rz, μm	
		Outer surface	Inner surface	Outer surface	Inner surface
11.5	1	-	-	-	-
	2	0.49	0.13	4.79	1.39
	3	0.47	0.18	5.38	2.06
	4	0.63	0.23	6.14	2.76
	6	0.73	0.26	6.47	2.9
	10	0.76	0.3	6.45	3.34
13	1	0.45	0.11	4.69	1.58
	2	0.46	0.26	4.63	2.67
	4	0.47	0.35	4.57	2.71
14	1	0.43	0.23	4.77	2.1
	2	0.61	0.24	5.73	2.13
	4	0.53	0.25	5.27	2.74

3. Results and discussion

Fig. 3a shows the change of the Ra parameter on both sides of tubes for different values of angles of floating plug β and drawing speeds. The greatest reduction in mean roughness occurs on the inner surface of the tube. There is also a tendency for the mean roughness value to increase with increasing drawing speed. There is no clear influence of the floating plug on the change of the Ra parameter value. The largest change in the initial mean roughness, for all angles of the floating plug, occurs on the inner surface of the thin-walled tube. Similar qualitative conclusions can be made regarding the influence of drawing speed and angle of floating plug on the ten point height of irregularities Rz (Fig. 3b). The larger the angle of floating plug β at a constant die angle α, the smaller the gap between the outer surface of the plug and the inner surface of the tube. It causes less lubricant to enter the deformation zone. At the same time, the contact area between the floating plug and the tube surface increases. This increases the friction between the contact surfaces and reduces the surface roughness of the inner surface of the tube.

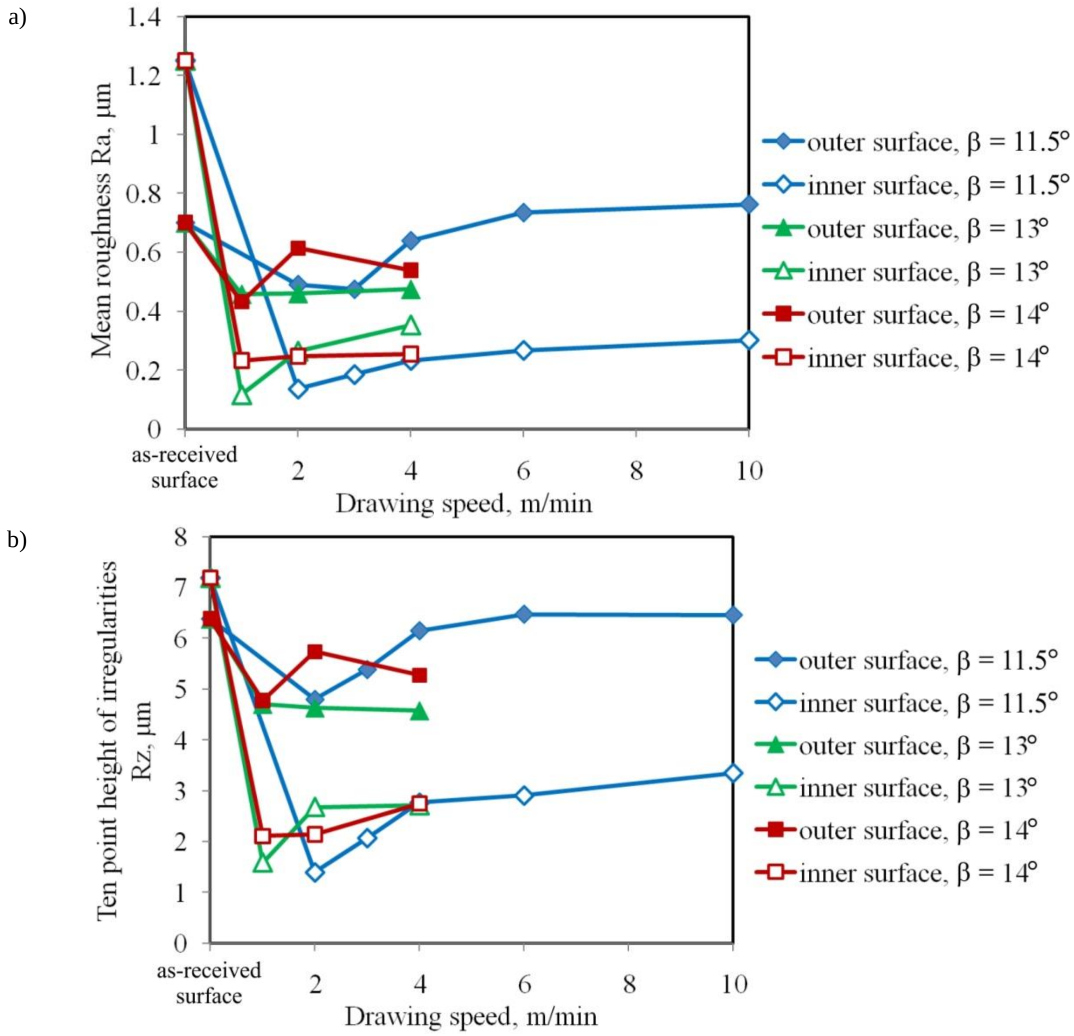

Fig. 3. Effect of drawing speed on the value of a) Ra and b) Rz parameters.

3.1. Mean roughness Ra

The Fisher test is a statistical test used to compare the variances of two population samples. The test is based on the F distribution, which is a probability distribution comparing the ratio of two variances. The F test was used to test the homogeneity of variance between multiple groups. It was used to determine whether the variances of two groups are equal or not.

The F-value of 66.04 determined using ANOVA implies the model is significant. Moreover, the *p*-value less that 0.0001 indicate model terms are significant. Angle of the floating plug ($p = 0.0004$) and location of mean roughness measurement on the tube surface ($p < 0.0001$) are also significant model terms. The difference between adjusted R^2 (0.861) and predicted R^2 (0.817) is less than 0.2. So, it can be concluded that these parameters are in statistically reasonable agreement.

The scatter plots presented in the Fig. 4 provide valuable insights into the dataset's characteristics. Fig 4a shows a positive correlation between the externally studentized residuals and the normal probability. This is evidenced by the data points closely aligning with the line of best fit. Fig. 4b illustrates the spread of externally studentized residuals against predicted values. Interestingly, the data points do not form any clear pattern or trend, indicating a random distribution of residuals. Fig 4c presents a strong positive correlation between actual and predicted values. The data points align closely with a diagonal line, indicating an effective model performance. This suggests that the model is accurately predicting the outcomes, which is a desirable attribute in predictive modeling.

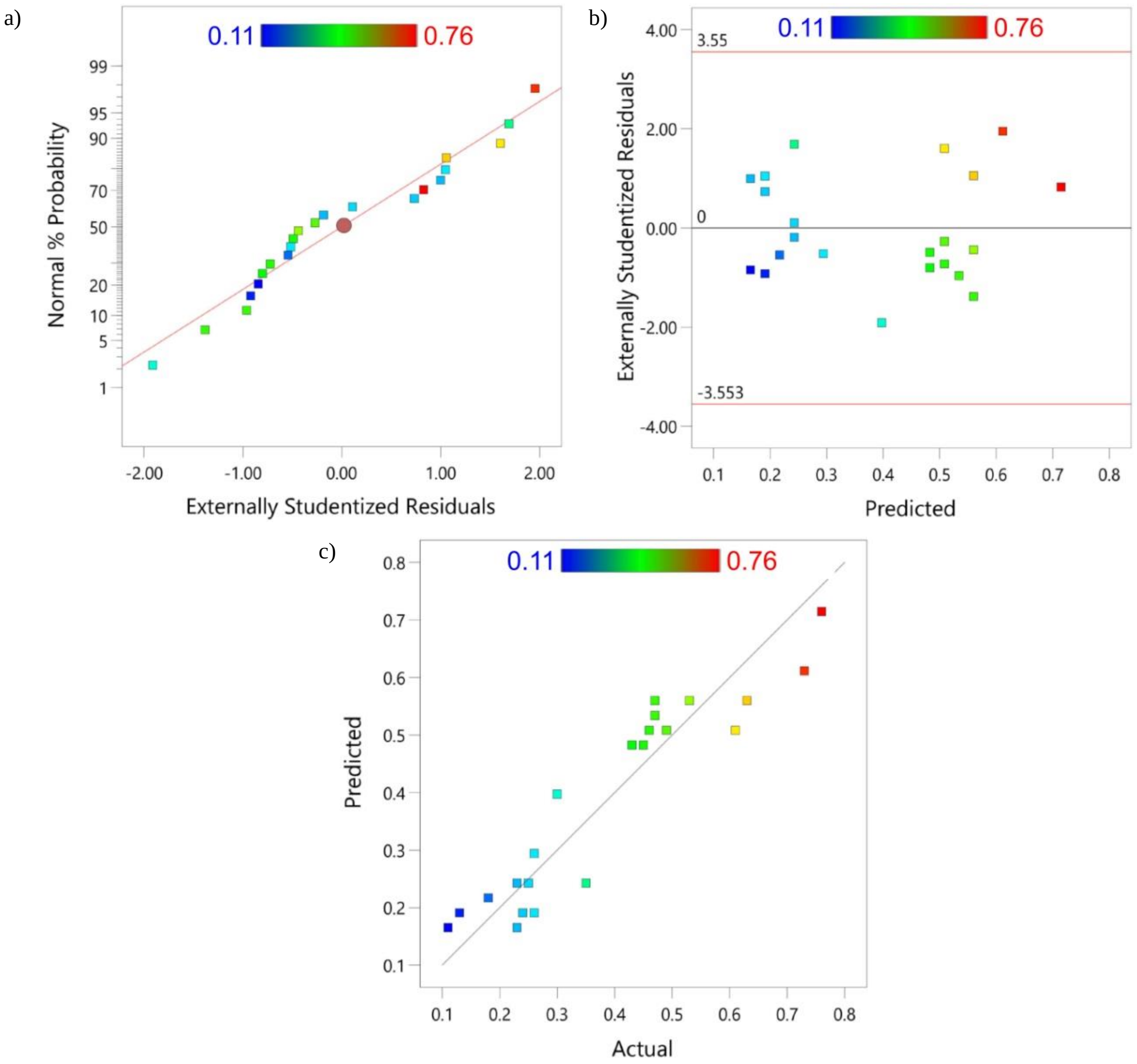

Fig. 4. a) normal probability plot, b) residuals with reference to predicted value of Ra parameter and c) predicted versus actual response for mean roughness Ra.

Based on the results of the ANOVA model, it can be concluded that the angle of floating plug in the range of β = 11.5-14° has no effect on the value of mean roughness Ra (Figs. 5, 6). Increasing the drawing speed increases the value of roughness parameter Ra. This character is almost the same for the Ra parameter measured at inner side (Fig. 5) and outer side (Fig. 6) of the tube. Increasing the drawing speed causes an increase in temperature in the contact zone and a change in the mechanical properties of the workpiece. Moreover, the temperature rise on the contact surface causes a thermal decomposition of the lubricant. Effect of sliding speed on the mean drawing force and the maximum temperature in the contact zone is shown in Fig. 7. At a drawing speed of 10 m/min, the temperature was reduced compared to the drawing speeds of 4 and 6 mm/min due to the fact that the tube did not reach a high temperature during drawing. Probably with a longer feed tube, at a speed of 10 m/min, the temperature would reach a higher value than for lower drawing speeds. The reduced amount of lubricant is the main factor for deterioration of surface roughness. Suliga (2014) found that the heat-affected surface layer becomes thicker with a decreased drawing speed. The FPD process greatly improved the inner surface quality of tube, which is in agreement with results by Yan et al. (2022).

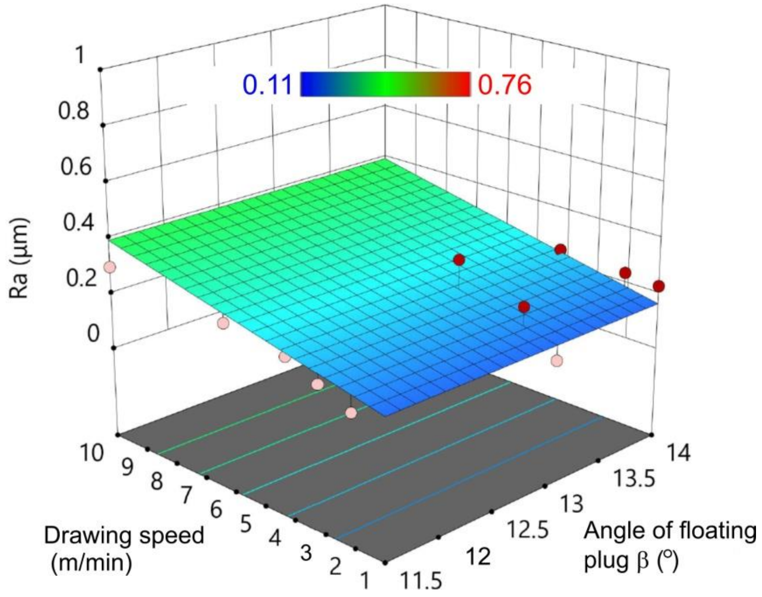

Fig. 5. Effect of angle of floating plug and drawing speed on the mean roughness Ra measured at inner side of the tube.

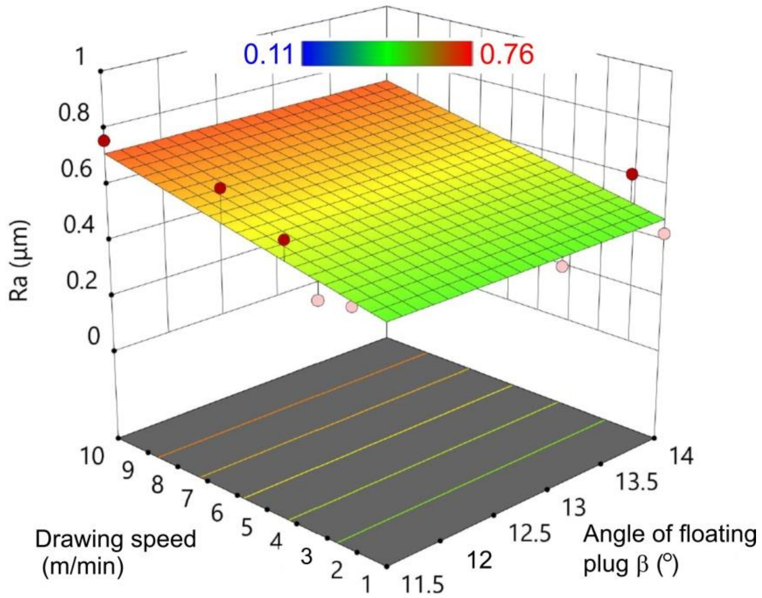

Fig. 6. Effect of angle of floating plug and drawing speed on the mean roughness Ra measured at outer side of the tube.

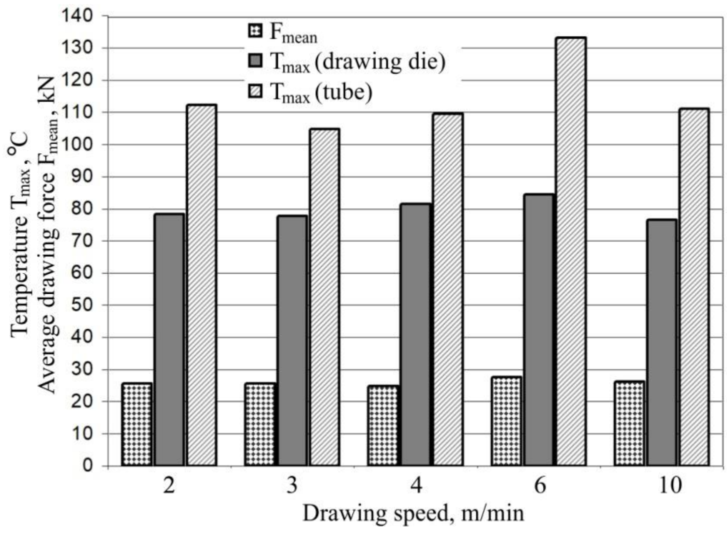

Fig. 7. Effect of drawing speed on the mean drawing force and the maximum temperature in the contact zone.

3.2. Ten point height of irregularities Rz

The F-value of 69.94 determined using ANOVA implies the model is significant. Moreover, the p-value less that 0.0001 indicate model terms are significant. Angle of the floating plug (*p* = 0.7063), location of measurement of ten point height of irregularities Rz on the tube surface (*p* < 0.0001) and product of drawing speed and angle of the floating plug (*p* = 0.0254) are also significant model terms. The difference between adjusted R^2 (0.942) and predicted R^2 (0.927) is less than 0.2. So, it can be concluded that these parameters are in statistically reasonable agreement.

Diagnostic plots in Fig. 8 presents perspective on the dataset's properties. Fig. 8a demonstrates a positive correlation between the externally studentized residuals and the normal probability. This is evidenced by the data points that closely follow the line of best fit. Fig. 8b plot showcases the distribution of externally studentized residuals against predicted values. The data points are scattered randomly, indicating a lack of any discernible pattern or trend. This randomness is a positive sign as it suggests that the model's assumptions are likely being met. Fig. 8c plot reveals a strong positive correlation between actual and predicted values. The data points closely align with a diagonal line, indicating that the model is performing well in its predictions. This is a desirable characteristic in predictive modeling.

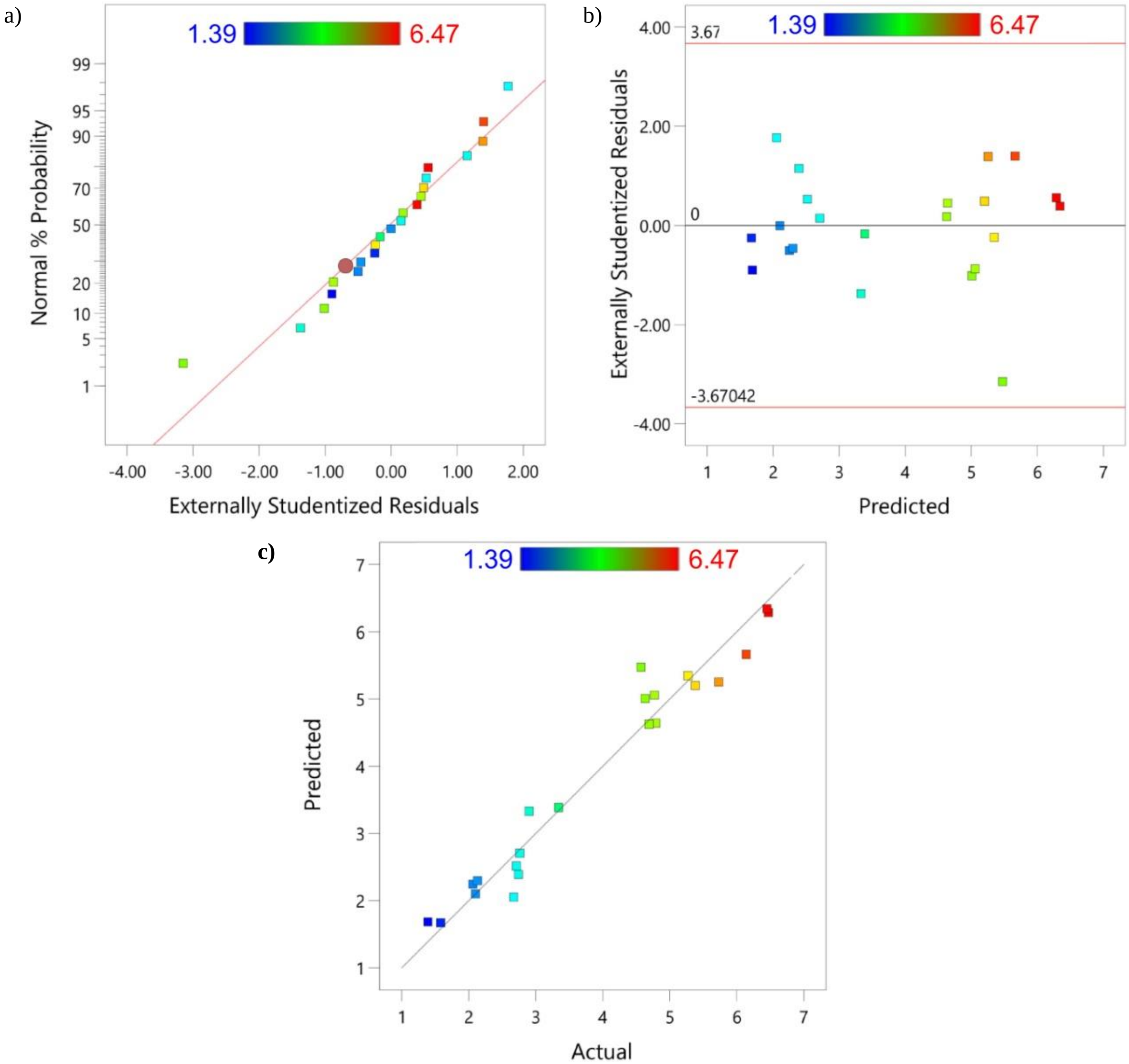

Fig. 8. a) normal probability plot, b) residuals with reference to predicted value of Rz parameter and c) predicted versus actual response for ten point height of irregularities Rz.

The influence of the angle of floating plug on the point height of irregularities Rz depends on the drawing speed (Figs. 9, 10). At low drawing speeds, the value of the Rz parameter increases as the angle of floating plug increases. At the highest sliding speed (10 m/min), increasing the angle of floating plug reduces the Rz parameter. The mentioned conclusions refer to the inner (Fig. 9) and outer (Fig. 10) surface of the tube. For the tool with the lowest value of the angle of floating plug, the value of the Rz parameter increases over the entire range of analyzed drawing speeds. At the angle of floating $\beta = 14°$, starting from a speed of approximately 4 m/min, the value of the ten point height of irregularities Rz decreases.

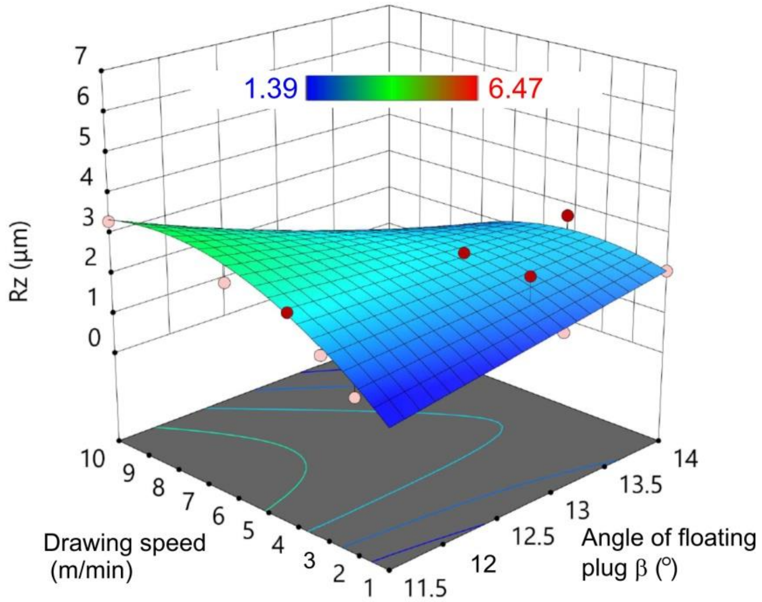

Fig. 9. Effect of angle of floating plug and drawing speed on the ten point height of irregularities Rz measured at inner side of the tube.

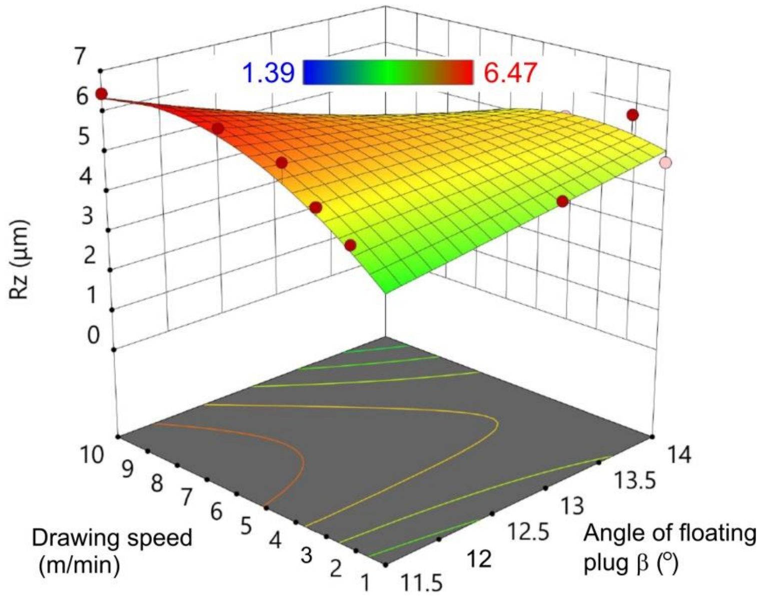

Fig. 10. Effect of angle of floating plug and drawing speed on the ten point height of irregularities Rz measured at outer side of the tube.

4. Conclusions

This article presents the results of the analysis of changes in the surface topography of AISI 321 thin-walled stainless steel tubes in floating-plug drawing process. Based on the analysis of variance presented in this article, the following conclusions can be drawn:

- The greatest reduction in mean roughness occurs on the inner surface of the tube. This suggests that the FPD process significantly improves the inner surface quality of the tube.
- There is a tendency for the mean roughness value to increase with increasing drawing speed. This is due to the increase in temperature in the contact zone and a change in the mechanical properties of the workpiece, which leads to a thermal decomposition of the lubricant.

- The angle of the floating plug β in the range of 11.5-14° has no effect on the value of mean roughness Ra. This indicates that the floating plug's angle does not significantly influence the roughness of the tube surface.
- The influence of the angle of the floating plug on the point height of irregularities Rz depends on the drawing speed. At low drawing speeds, the value of the Rz parameter increases as the angle of the floating plug increases, while at the highest sliding speed, increasing the angle of the floating plug reduces the Rz parameter.

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Wpływ Procesu Ciągnienia na Korku Swobodnym na Wykończenie Powierzchni Wewnętrznej i Zewnętrznej Rur Cienkościennych Wykonanych ze Stali Nierdzewnej AISI 321

Streszczenie

W artykule przedstawiono wyniki analizy zmian topografii powierzchni rur cienkościennych ze stali nierdzewnej AISI 321 po procesie ciągnienia na korku swobodnym. Badania eksperymentalne przeprowadzono w jednym przejściu, ze zmienną prędkością ciągnienia (1, 2, 3, 4, 6, and 10 m/min) oraz różnymi kątami β korka swobodnego (11.3°, 13° and 14°). W badaniach eksperymentalnych wykorzystano smar Wisura DSO7010 (Fuchs Oil). Jako wskaźniki jakości powierzchni przyjęto średnie arytmetyczne odchylenie rzędnych profilu Ra oraz wysokość chropowatości według 10 punktów Rz. Parametry chropowatości mierzono niezależnie na wewnętrznej i zewnętrznej powierzchni rur cienkościennych. Do analizy związków pomiędzy parametrami procesu ciągnienia (prędkość ciągnienia i kąt korka swobodnego) wykorzystano analizę wariancji. Zaobserwowano zmniejszenie wartości obydwu analizowanych parametrów chropowatości w wyniku procesu ciągnienia. Proces ciągnienia na korku swobodnym znacznie poprawia jakość wewnętrznej powierzchni cienkościennych rur ze stali nierdzewnej AISI 321. Zaobserwowano tendencję do zwiększania się parametru Ra wraz ze wzrostem prędkości ciągnienia, podczas gdy kąt β korka swobodnego nie miał znaczącego wpływu na średnią chropowatość Ra.

Słowa kluczowe: analiza wariancji, korek swobodny, stal nierdzewna, chropowatość powierzchni, ciągnienie rur