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Experimental and statistical investigation of thermo-mechanical friction drilling process

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1. Introduction

One of the actual problems in the manufacturing engineering is related to the assembly of the sheet metals, thin-walled tubes or profiles. These tasks could be performed using friction drilling technology, which enable to simplify assembly process and to improve reliability of the joint.

Friction drilling is nontraditional metal treatment method, used to produce holes in the thin-walled sheet metal for assembly of various structural elements. This method enables to eliminate additional manufacturing like welding countless nuts or assembly using J-nuts.

A rotating punch-type tool is forced into the material, the heat generated by the friction, heats the surrounding area, the material become plastic and forms cylindrical hole without metal removal. The tool penetrated into the material pierce a hole and the excess of the material forms the neck on the underside and collar on the upside of the sheet, increasing the wall thickness and strength of a hole.

Typical friction drilling steps and the movements subjected to the tool are showed in Fig. 1.

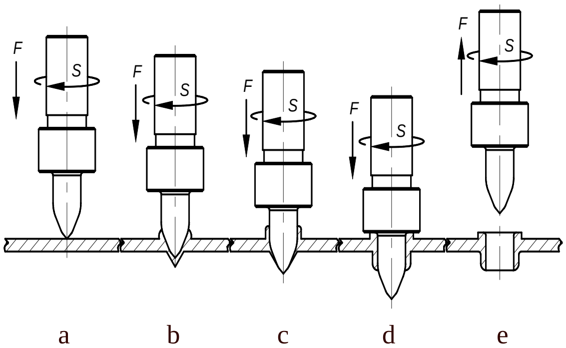


Fig. 1 Friction drilling steps: a - initial contact; b - tool-tip penetration to the material; c - material flow; d - collar forming; e - tool withdrawal

Friction drilling process investigation overview has showed that during drilling workpiece temperature can increase up to 600ºC and tool – up to 650-750ºC [1-3], meanwhile tool penetration force depends on drilling regimes and shape of the tool and various in very large limits.

However, the influence of mechanical properties and chemical composition of the materials on drilling process, as complex, is not investigated.

The aim of this work was to investigate the influence of materials mechanical properties, drilling regimes and plate thickness on axial drilling force and torque in order to optimise drilling regimes.

2. Materials and workpieces

The experiment was performed using three various sheet materials: - hot rolled S235 steel, AISI 4301 stainless steel and Al 5652 aluminium alloy. The chemical composition, mechanical properties and dimensions of the workpieces are presented in Tables 1-3.

Table 1

Chemical composition of as-received sheet metal

Element, wt %	S235	AISI 4301	Al 5652
C	0.2	0.08	-
Si	1.0	-	0.25
Mn	1.0	-	0.011
Cr	-	0.17	0.2
Ni	0.5	-	-
Mg	-	-	2.2-2.8
Cu	-	-	0.04
Zn	-	-	0.25
P	0.04	0.04	-
Fe	-	-	0.4
Ti	-	-	0.2

Table 2

Mechanical properties of the metal

Material	Ultimate strength σ_u, MPa	Yield limit σ_y, MPa	Elongation A_5, %
S235	430	245	20
AISI 4301	395	225	26
Al 5652	195	65	19

Table 3

Workpieces dimension, mm

Material	Thickness	Length	Width
S235	2.5	350	60
AISI 4301	1.5		
	2		
Al 5652	1.5		

3. Experimental technique

The experiment was performed on a CNC milling machine “DMU-35M” with controller “Sinumerik 810D/840D” using tungsten carbide tool with diameter of 5.4 mm. The shape of the tool is showed in Fig. 2, dimensions - in Table 4.

Drilling program was written using “Shop Mill” software, which enable to simulate drilling time and to change drilling regimes in expeditiously manner.

Table 4

Dimensions of the friction drill, mm

*D*1	*D*2	*D*3	*L*1	*L*2	*L*3	*L*4	*L*5	*R*	*θ*°
5.4	8	11	11	14	7	5	6	0.5	30

During the experiment drilling force was measured using rearranged standard force dynamometer DOSM-1M, the measurements results were recorded to the computer via oscilloscope “PICO ADC-212 (Fig. 3).

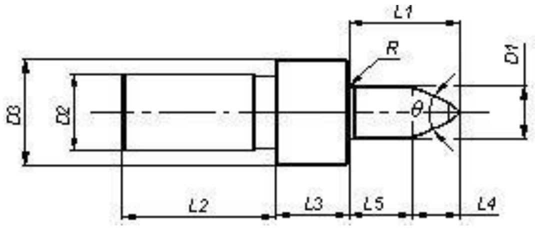


Fig. 2 Shape of the friction drilling tool

a

b

Fig. 3 Friction drilling experimental set up: a - overview; b - drilling device

4. Experimental results

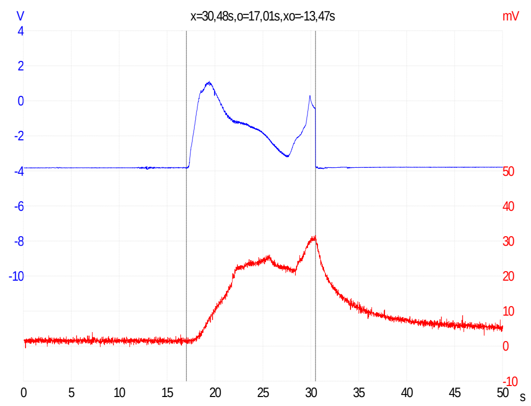
The experiment was planned according the course: spindle rotational speed set of 2000, 2500 and 3000 rpm was selected and for each ones drilling feed ratio set of 60, 100 and 140 mm/min was assigned.

The analysis of the experimental data showed that axial force, from the initial contact to the collar forming, varies in very large limits.

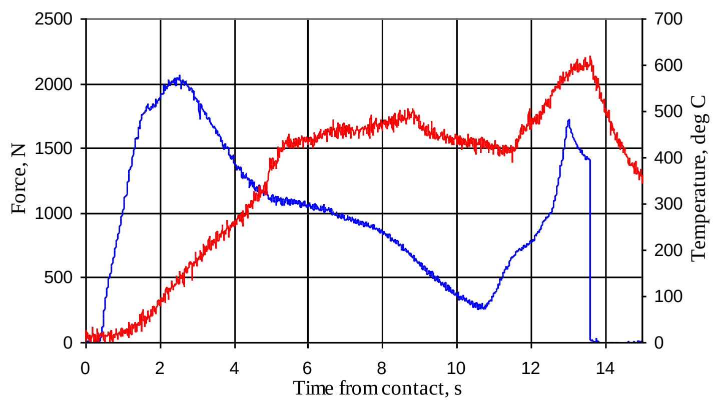
The example of force and temperature records and the same records presented in the force and temperature units are showed in Fig. 4.

It was defined that independently of cutting regimes, forming force reaches its maximal value when the conical section of the drill penetrates into the material (“c”- step, Fig. 1); when the sheet is pierced, the actual force drastically decreases (“d”- step) and increases again when the collar on the upper sheet surface is formed (“e”- step).

The experimental curves of the axial force variation during drilling for hot rolled S235 steel is presented in Fig. 5, for AISI 4301 stainless steel - in Figs. 6 and 8 and for Al 5652 aluminium alloy - in Fig. 9.

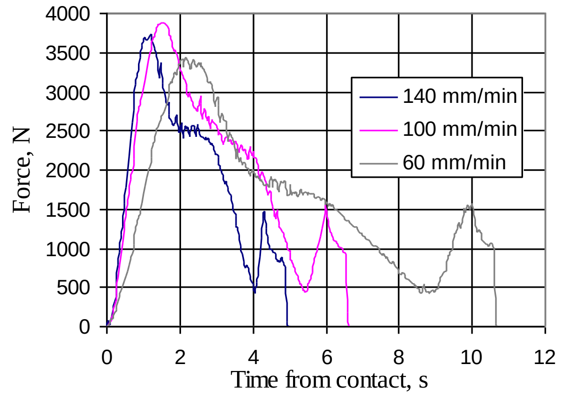


a



b

Fig. 4 Example of friction drilling record: a - top graph - force, under graph - temperature records; b - the same records in force (N) and temperature (°C) units



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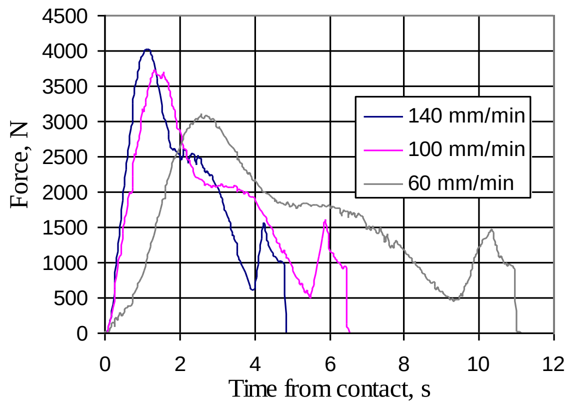

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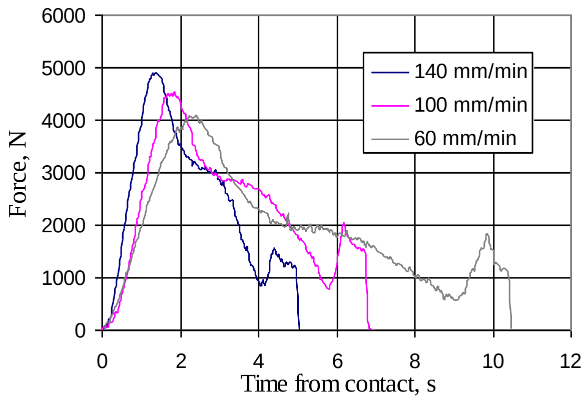


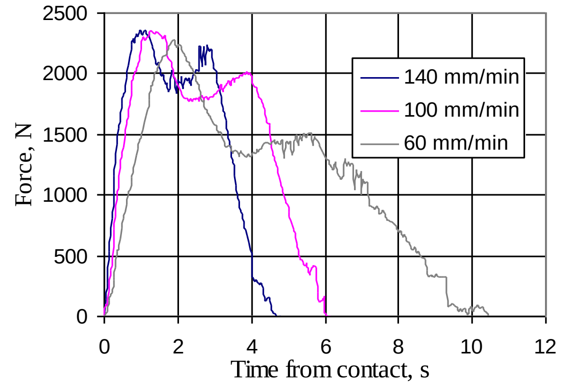
c

Fig. 5 Axial force variation for S235 steel: a - 2000 rpm; b - 2500 rpm; c - 3000 rpm

It was founded that maximal drilling force F_{max} proportionally depends on feed ratio *FR* and sheet thickness t: - the bigger *FR* and t calls bigger forming force and conversely depends on rotational speed *S*, because higher drilling speed causes higher temperature in the contact zone between tool and workpiece, as a result the piercing force is needed lower.

The actual drilling torque was not measured, therefore for ones calculation, special experiment comprised step by step holes drilling in the plates with the thickness of 1, 1.5 and 2 mm, with the feed step of 0.5 mm was performed. Thereafter, the plates using wire electro-discharge machining technology (EDM) were cut throw the centres of the holes in order to define actual surface contact area between workpiece and tool (Fig. 7).

Referring to [1, 2], it was defined that maximal torque results when the tool conical section is fully pierced into the sheet, therefore drilling torque was calculated using truncated cone model (Fig. 10).



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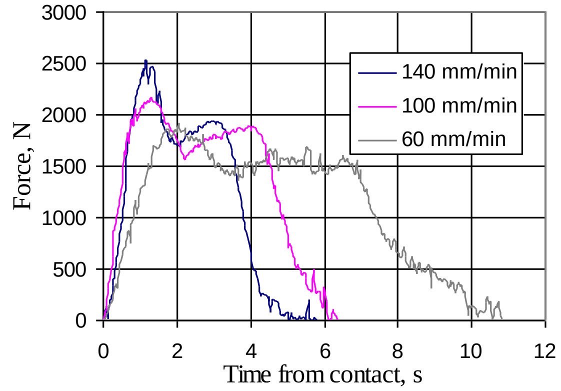

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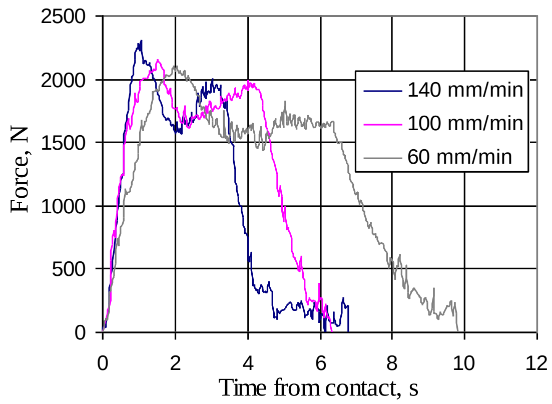

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Fig. 6 Axial force variation for AISI 4301 steel (sheet thickness 1.5 mm: a - 2000 rpm; b - 2500 rpm; c - 3000 rpm

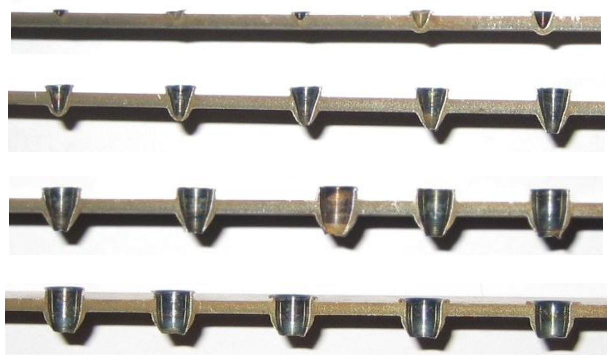
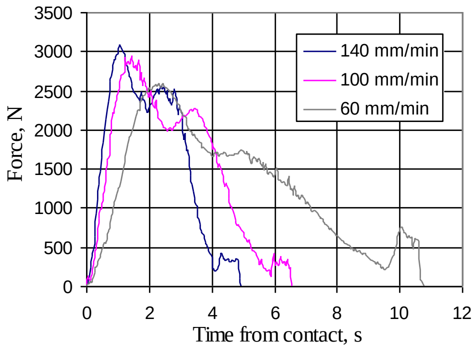


Fig. 7 Cross-section of the holes in S235 steel plate after step by step of 0.5 mm drilling



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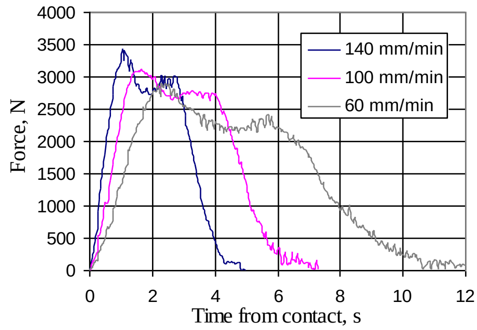

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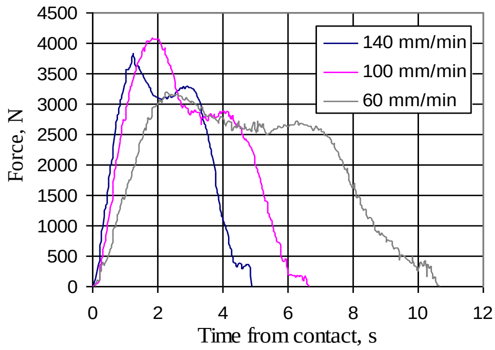


c

Fig. 8 Axial force variation for AISI 4301 stainless steel (sheet thickness 2 mm): a - 2000 rpm; b - 2500 rpm; c - 3000 rpm

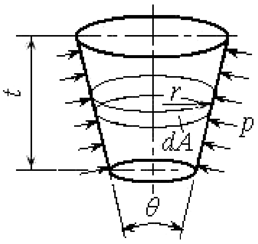


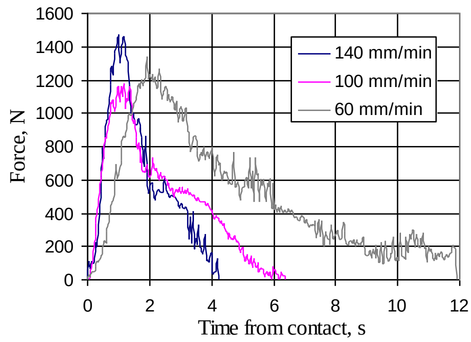
Fig. 10 Torgue calculation scheme for truncated cone

Equations for axial force F and torque T for truncated conical surface are expressed

$$F = 2\pi p\left(\int_0^t \sin\frac{\theta}{2}dA + \int_0^t \mu \cos\frac{\theta}{2}dA\right) \quad (1)$$

$$T = \int_0^t \mu prdA = \frac{2\pi\mu pt^3 \tan^2\frac{\theta}{2}}{3\cos\frac{\theta}{2}} \quad (2)$$

where t is the plate thickness, mm; μ is friction coefficient; p is the pressure in the contact zone, MPa; r is the surface radius, mm; θ is the angle of truncated conical section (θ = 30°); A is the contact surface area between tool and workpiece.



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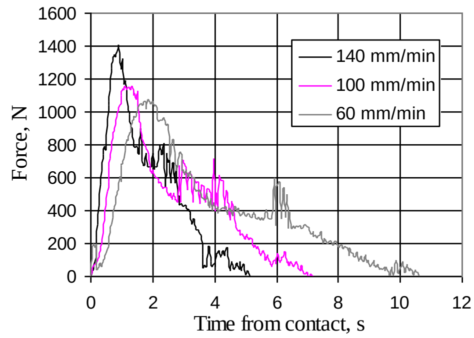

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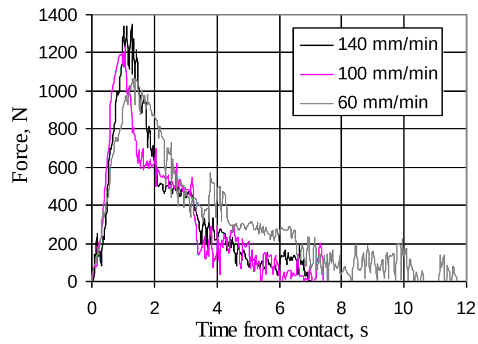

c

Fig. 9 Axial force variation for Al 5652 aluminium alloy: a - 2000 rpm; b - 2500 rpm; c - 3000 rpm

The value of friction coefficient was set 0.4 for steel and 0.5 - for aluminium alloy [2-5]; the pressure was calculated from the yield stress condition in the contact zone.

5. Design of experiment

In this stage of investigation, the influence of drilling regimes and mechanical properties of the materials to the maximal axial force F_{max} and torque T_{max} was performed.

In order to obtain the relationship of mechanical properties and drilling regimes on drilling parameters F_{max} and T_{max} and to obtain regression model which in the best way could explain mechanical properties of the materials and drilling parameters influence on axial force F_{max} and torque T_{max} variation, the multivariable regression analysis was carried out.

Experimental matrix, on which base regression analysis was performed, is presented in Table 5.

Table 5

Experiment matrix and results

Material grade	Thickness t, mm	Spindle speed S, rpm	Feed ratio, mm/min	Axial force F_{max}, N	Torque T_{max}, Nm
S235	2.5	2000	60	4892	1.76
			100	4469	2.08
			140	4072	2.52
		2500	60	3401	2.45
			100	3877	2.52
			140	3741	2.39
		3000	60	3122	2.49
			100	3712	2.53
			140	4010	2.42
AISI 4301	1.5	2000	60	2319	2.32
			100	2401	2.53
			140	2422	2.50
		2500	60	2126	2.42
			100	2172	2.53
			140	2305	2.53
		3000	60	1951	2.40
			100	2187	2.51
			140	2477	2.53
AISI 4301	2.0	2000	60	3140	2.24
			100	4092	1.89
			140	3752	1.30
		2500	60	2954	2.46
			100	3156	2.12
			140	3497	1.70
		3000	60	2629	2.45
			100	2898	2.50
			140	3149	2.29
Al 5652	1.5	2000	60	1202	1.07
			100	1181	1.17
			140	1344	1.17
		2500	60	1128	1.07
			100	1161	1.17
			140	1358	1.17
		3000	60	1091	0.86
			100	1293	0.92
			140	1232	1.17

Statistical evaluation of the experimental data was performed using „Excel“ function „Data Analysis“, which performs error of estimate, average deviation, maximum deviation for any observation, explained proportion of variance (R^2), adjusted coefficient of multiple determinations, F-value, Prob. (F), Prob. (t) and performs analysis of variances. Estimation of applicability of used models was based on the coefficient of maximum deviation R^2 and F-value, because these parameters are acceptability criteria of model adequacy to the experimental data.

If the intervals of factors variation are tenuous, iterations can be limited by linear approximation

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + \ldots + a_nX_n \tag{3}$$

where a_n are unknown parameters of the model (regression coefficients); $n = 1,\ 2,\ 3, \ldots, i$ are the factors of influence; $X_1, X_2, X_3, \ldots, X_I$ are independent variables.

Referring to this, regression analysis was performed making presumption that drilling force and torque are stipulated as the entirety of mechanical properties of the materials - yield limit σ_y and ultimate strength σ_u, drilling regimes - spindle rotational speed S and feed ratio FR and sheet thickness t as total action of them and could be expressed by five variable regression model for F_{max} and T_{max} respectively

$$F_{max} = a_0 + a_1\sigma_y + a_2\sigma_u + a_3S + a_4FR + a_5t \tag{4}$$

$$T_{max} = b_0 + b_1\sigma_y + b_2\sigma_u + b_3S + b_4FR + b_5t \tag{5}$$

Summary output, analysis of variance, parameter values and comparative five variable linear regression analysis for maximal axial drilling force and torque are presented in Tables 6 and 7.

Table 6

Regression statistics of mechanical properties and drilling regimes influence on axial force and torque

	F_{max}	T_{max}
Multiple R	0.96	0.92
R Square	0.91	0.84
Adjusted R Square	0.90	0.82
Standard Error	345	0.26
Observations	36	

Table 7

ANOVA for mechanical properties and drilling regimes

Factor	*df*	*SS*	*MS*	*F*	*Significance F*
For axial force F_{max}					
Regression	5	3.82E7	7.63E7	64.0	4.27E-15
Residual	30	3.58E6	1.19E5		
Total	35	4.17E7			
For torque T_{max}					
Regression	5	10.74	2.15	32.1	3.52E-11
Residual	30	2.01	0.067		
Total	35	12.74			

Regression analysis showed that five variable linear regression model with 96% probability describes experimental F_{max} data and the hypothesis of influence of the factors, introduced into regression model with 5% significance level is accepted, because $F_{max} = 64.0 > F_{0.05} = 2.901$.

The same regression analysis with respect to drilling torque T_{max} showed similar probability results: R^2=0.84 and $F = 32.1 > F_{0.05} = 2.901$.

Research enabled to conclude that presented models Eqs. (6) and (7) with 95% and 92 % probability for F_{max} and T_{max} respectively (confidence coefficient α=0.05), reasonably explain experimental data variation, so drilling force F_{max} and torque T_{max} dependence upon material mechanical properties, drilling regimes and thickness of the workpiece can be expressed

$$F_{max} = 3023 + 65.2\sigma_y - 46.4\sigma_u - 0.172S + 3.55FR + 1979t \tag{6}$$

$$T_{max} = -3.29 - 0.049\sigma_y + 0.046\sigma_u - 1.63\cdot10^{-5}S - 3\cdot10^{-4}FR - 0.74t \tag{7}$$

ANOVA results showed that sheet thickness, yield limit and feed ratio are significant parameters that most intensively affect F_{max}; meanwhile T_{max} significantly influences feed ratio and material mechanical properties - yield limit and ultimate strength. Contrary to expectation, spindle rotational speed has no valuable influence on drilling regimes variation.

The coincidence of the experimental and calculated F_{max} and T_{max} values enabled to conclude that regression models Eqs. (6) and (7) could be used to optimise friction drilling process for wide spectrum of the structural materials.

6. Conclusions

The investigation of friction holes drilling with various cutting regimes showed that biggest drilling force was given when conical section of the tool penetrates into the sheet; when the sheet is pierced force significantly decreases, but torque reaches its maximal value.

The analysis of spindle rotational speed influence on axial force variation showed that minimal spindle speed (2000 rpm) calls bigger drilling force in compare to the higher speed (2500 and 3000 rpm); drilling feed influence on axial force and torque variation analysis showed that than bigger feed - than bigger axial force. The experiment showed that drilling force considerably depends on sheet thickness; therefore it should be considered optimising friction drilling process.

Probabilistic investigation of the influence of mechanical properties of the materials (σ_y, σ_u), drilling regimes - tool rotational speed S, feed ratio FR and sheet thickness t on drilling parameters F_{max} and T_{max} showed, that proposed five variable linear regression model reasonably explain axial force F_{max} and torque T_{max} variation. ANOVA showed that sheet thickness t, feed ratio FR and yield limit σ_y are significant parameters that most intensively affect F_{max} and T_{max}, however spindle rotational speed S has less valuable influence.

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P. Krasauskas

TERMOMECHANINIO FRIKCINIO GRĘŽIMO PROCESO EKSPERIMENTINIS IR STATISTINIS TYRIMAS

Reziumė

Straipsnyje pateikiamas termomechaninio frikcinio gręžimo proceso eksperimentinis tyrimas ir analizė, aprašoma eksperimentinė frikcinio gręžimo metodika, pateikiami skirtingų medžiagų - karštai valcuoto plieno S235, nerūdijančio plieno AISI 4301 ir aliuminio lydinio Al 5652 frikcinio skylių gręžimo eksperimentinio tyrimo rezultatai ir analizė. Medžiagų mechaninių charakteristikų, gręžimo režimų ir ruošinio storio įtakos, gręžimo jėgos ir momento kitimui įvertinti buvo atlikta statistinė penkių nepriklausomųjų kintamųjų regresinė analizė ir nustatytas priežastinis jų tarpusavio ryšys. Pasiūlyti daugiafaktoriniai tiesinės regresijos modeliai gręžimo procesui optimizuoti.

P. Krasauskas

EXPERIMENTAL AND STATISTICAL INVESTIGATION OF THERMO-MECHANICAL FRICTION DRILLING PROCESS

Summary

This paper deals with the experimental investigation and analysis of the thermo-mechanical friction drilling process. Experiment technique is presented and described; experimental results of the thermo-mechanical friction drilling for hot rolled S235 steel, AISI 4301 stainless steel and Al 5652 aluminium alloy are presented and discussed. Statistical five variable linear regression analysis was performed in order to evaluate the influence of mechanical properties of the materials, drilling regimes and workpiece thickness on maximal drilling force and torque variation. Proposed multivariable linear regression models to optimise drilling process.

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