MATHEMATICAL MODELS FOR THE ANALYSIS OF THE PARAMETERS OF CHANNELS IN THE PLANNING OF MECHANICAL PROCESSING AND WELDING OPERATIONS

Volodymyr Shanaida [1], Ruslan Skliarov [1] and Valeriy Lazaryuk [1]

[1] *Ternopil Ivan Puluj National Technical University, Ruska str., 56, Ternopil, 46001, Ukraine*

Abstract

The introduction and use of information technologies is an integral part of the successful functioning of modern production. The analysis of the production processes of individual enterprises made it possible to determine specific requirements for planning their production activities. In many cases, planning departments create their own intellectual and informational systems for comprehensive planning of the production process even when accepting a production order. We have proposed a series of mathematical models for describing the geometric parameters of the part, which have a significant impact on the indicators of the energy consumption of the production process and the costs of performing assembly operations. Mathematical models are obtained by implementing a non-linear regression algorithm of a general type. The adequacy of mathematical models was checked by the value of the coefficients of determination R^2 for the proposed approximating functions and input sets of discrete data.

Keywords

band saw technologies, rolled section, mathematical modeling, information systems, welding operation

1. Introduction

The use of profile blanks for the manufacture of body and frame structures involves the analysis of several technical and economic indicators. Among the technical indicators, it is worth noting such as the cross-sectional area of the profile, and among the technical and economic ones, the indicator for accounting for the length of the weld seam. The first indicator has the significance of the choice of equipment to ensure the mechanical processing of the used profile, and, accordingly, the power consumed per unit of time. The second indicator indicates the actual costs of consumables and the time required to perform a welding operation by an employee of a particular qualification. These indicators have a direct impact on the employee's salary.

In modern blank production, about 80% of blanks are cut using band saw technologies. These technologies are high-tech, high-performance energy and resource-saving processes. Band sawing technologies cover a wide range of workpiece cross-sections - from sheets with a thickness of 0.5 mm to rolled products of 1.5 m. Band saws process steel blocks, long products, hard-to-cut steels, nickel-based and titanium-based alloys, non-ferrous metals and their alloys, granite, concrete, and other materials of various shapes and sizes.

2. Related works

A lot of researchers have been studying how band saws perform when used for machining. They've been focusing on a few key areas, including analyzing the temperature in the cutting zone [1], looking

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EMAIL: Shanayda-vv@ukr.net (A. 1); kalibr2011@gmail.com (A. 2); lazaryuk@gmail.com (A. 3)
ORCID: 0000-0002-9743-9110 (A. 1); 0000-0001-6112-964X (A. 2); 0000-0003-3731-2828 (A. 3)

at different types of dynamic loads and how they affect the process [2], and examining how different geometric parameters and the quality of the metal being cut impact energy costs [3, 4]. Another important factor in this type of machining is the shape of the chip created by the cut layer, which can have a big impact when working in tight spaces [5]. This issue has been studied in various forms regarding the impact of geometric parameters of the sheared metal layer on the power consumed during mechanical processing [6]. Numerous articles have identified cutting power as the primary indicator of energy consumption during processing procedures [7-9]. Band saws typically indicate the recommended thickness and height, among other technical characteristics [10,11]. Altering the cross-sectional area for specified saw blade parameters will significantly affect the consumed cutting power [12].

When planning a welding operation, it's crucial to consider the cross-sectional area and perimeter of the channel. These parameters are necessary for calculating welding modes and working time. The goal is to ensure that the welded structure has the same strength as the original material. To achieve this, it's important to analyze the softening heat-affected zone parameters in the welded joint. The geometric parameters of this zone are determined by the cross-sectional area and perimeter of the rolling products section [13, 14].

In order to determine how long it will take to weld each piece, we must combine the main arc burning time and auxiliary time. The main arcing time is proportional by the size of the weld's cross-section and inversely proportional by the arc current. The auxiliary time considers the length of the weld and the number of passes required, which are determined by the cross-section size. If the channel's cross-sectional area changes, the welding time will also change. It's important to note that the welding speed is inversely affected by the cross-sectional area of the seam [15].

Welded joints of channels often use butt seams. This type of connection is practical, straightforward, and cost-effective. Welding is typically done from both sides to ensure adequate depth of penetration. However, creating a proper edge preparation can be challenging for butt joint profiles, as incomplete penetration can occur at the entrance corners. For low-stress structures with shaped profiles, overlapping strapped butt joints are preferred. It's important to note that welding the strapping causes a significant stress concentration due to the sudden change in the joint's cross-section [14].

In certain situations, the structure can be put under too much stress due to the active loads, causing the weld's tensile strength calculation to be exceeded. To address this task, welded beams are assembled for stretched belts of structures to make assembly joints. An oblique butt joint is created during this welding operation, which is just as strong as the main section of the beam. To ensure it's strong enough, you can use information about the cross-sectional area of the channel in the oblique joint to select the optimal angle of inclination [16].

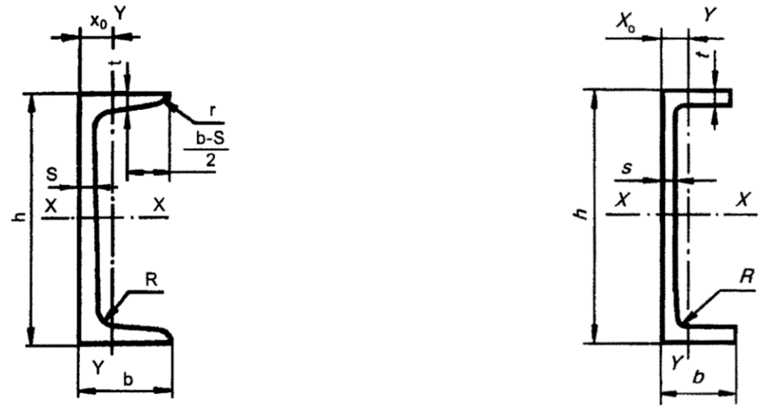
The advancement of production processes through automation and the creation of automated production preparation systems [17] requires the implementation of mathematical models to formalize technology and management tasks. Additionally, intelligent information systems and technologies rely on mathematical models of varying degrees of difficulty, making the development and verification of such models a pressing matter.

3. Proposed methodology

During the research, non-linear regression of the general type, with 3D modeling and discrete set analysis algorithms was used.

4. Results

According to DSTU 3436-96 "Hot-rolled steel channels (Rolling products)" the channel's geometric profile is determined by its dimensional characteristics (Fig. 1, a) and mass-geometric indicators (Fig. 1, b).



embodiment 1 embodiment 2

a)

Channel number of the U series	h	b	s	t	R	r	Cross-sectional area, F, sm^2	Mass from 1 m, kg	Reference values for axes							X_o, sm
					no more				X–X				Y–Y			
	mm								I_x, sm^4	W_x, sm^3	i_x, sm	S_x, sm^3	I_y, sm^4	W_y, sm^3	i_y, sm	
5У	50	32	4,4	7,0	6,0	2,5	6,16	4,84	22,8	9,1	1,92	5,59	5,61	2,75	0,95	1,16
6,5У	65	36	4,4	7,2	6,0	2,5	7,51	5,90	48,6	15,0	2,54	9,00	8,70	3,68	1,08	1,24
8У	80	40	4,5	7,4	6,5	2,5	8,98	7,05	89,4	22,4	3,16	23,30	12,80	4,75	1,19	1,31
10У	100	46	4,5	7,6	7,0	3,0	10,90	8,59	174,0	34,8	3,99	20,40	20,40	6,46	1,37	1,44
12У	120	52	4,8	7,8	7,5	3,0	13,30	10,40	304,0	50,6	4,78	29,60	31,20	8,52	1,53	1,54
14У	140	58	4,9	8,1	8,0	3,0	15,60	12,30	491,0	70,2	5,60	40,80	45,40	11,00	1,70	1,67
16У	160	64	5,0	8,4	8,5	3,5	18,10	14,20	747,0	93,4	6,42	54,10	63,30	13,80	1,87	1,80
16аУ	160	68	5,0	9,0	8,5	3,5	19,50	15,30	823,0	103,0	6,49	59,40	78,80	16,40	2,01	2,00
18У	180	70	5,1	8,7	9,0	3,5	20,70	16,30	1090,0	121,0	7,24	69,80	86,00	17,00	2,04	1,94
18аУ	180	74	5,1	9,3	9,0	3,5	22,20	17,40	1190,0	132,0	7,32	76,10	105,00	20,00	2,18	2,13

b)

Figure 1: The part configuration and mass-geometrical adjectives of the channel

In this article, we consider two main parameters: b, which represents the width of the channel shelf, and h, which represents the height of the channel. When constructing frame structures and trusses, there are two options for cutting the channel profile. The first option involves cutting along the channel shelf, and the height of the channel remains unchanged. The second option involves cutting along the profile height, and the width of the shelf remains unchanged.

In both cases, depending on the size of the cutting angle (displacement of the cutting blade of the saw along one of the geometric parameters), we get the values of the areas and perimeters, which will not be proportional to the values of the areas and perimeters in the normal section according to the right triangle rule. The angle value affects the resulting area and perimeter measurements non-proportional. Therefore, it is advisable to perform a study of changes in areas and perimeters for both cases regarding the most frequently used channel numbers both in general mechanical engineering and in other branches of economic activity.

4.1. The research and analysis alterations in the cross-sectional area and perimeter while displacement along the channel shelf

When moving the saw along the shelf of channel number 5U, which is manufactured according to DSTU 3436-96 " Hot-rolled steel channels (Rolling products)" (Fig. 2)

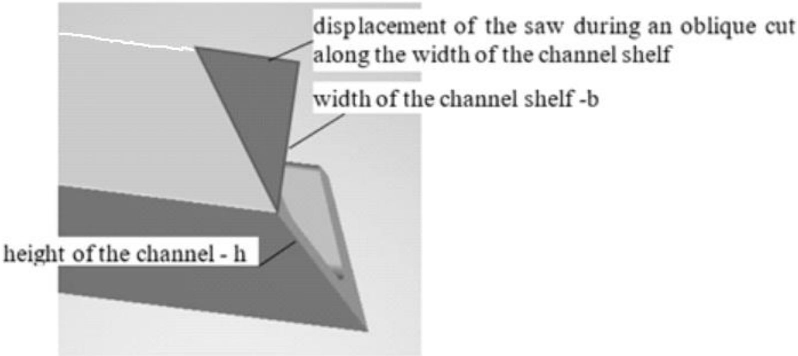


Figure 2: The scheme of the displacement of the saw during an oblique cut along the width of the channel shelf

the value of the cross-sectional area depending on the amount of displacement along the channel shelf can be described by the equation:

$$Pl(x) = 1.559 \cdot x^{1.559} - 2.684 \cdot x + 626.714$$

where x - displacement, mm.

After estimating the values of the studied parameter according to the proposed dependence, a comparison of the areas of the sheared layer with the actual indicators was carried out (see Table 1).

Table 1

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	15	20	25	32
Cross-sectional area:						
Actual, mm^2	626.689	656.576	692.123	739.022	795.266	886.272
Estimated, mm^2	626.714	656.271	692.552	739.158	794.833	886.419
Relative error, %	4.008e-3	0.046	0.062	0.018	0.054	0.017

For the same channel, the equation of describing the perimeter of a channel's cross-section varies based on the displacement along the shelf of the channel too:

$$Per(x) = 0.105 \cdot x^{1.608} - 0.201 \cdot x + 149.708$$

After estimating the values of the studied parameter according to the proposed dependence, a comparison of the perimeters of the sheared layer with the actual indicators was carried out (Table 2).

Table 2

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	15	20	25	32
Perimeter:						
Actual, mm	208.918	214.427	220.989	229.661	240.081	256.982
Estimated, mm	208.923	214.372	221.066	229.686	240.003	257.00
Relative error, %	2.199e-3	0.026	0.035	0.011	0.032	0.01

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.997	0.997

Other standard channel sizes were also studied:

- Channel №6.5U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.478 \cdot x^{1.572} - 2.686 \cdot x + 762.796$$

The outcomes of measurements and computations have been condensed into a table 3.

Table 3

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	15	20	25	30	36
Cross-sectional area:							
Actual, mm^2	762.737	791.617	826.298	872.540	928.616	992.861	1078.673
Estimated, mm^2	762.796	791.077	826.797	872.993	928.426	992.243	1.079e3
Relative error, %	7.70e-3	0.068	0.06	0.052	0021	0.062	0.031

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.244 \cdot x^{1.582} - 0.444 \cdot x + 254.314$$

The outcomes of measurements and computations have been condensed into a table 4.

Table 4

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	15	20	25	30	36
Perimeter:							
Actual, mm	254.304	259.282	265.266	273.255	282.958	294.091	308.988
Estimated, mm	254.314	259.19	265.35	273.332	282.926	293.987	309.045
Relative error, %	3.957e-3	0.035	0.032	0.028	0.011	0.035	0.018

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.996	0.996

- Channel №8U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.406 \cdot x^{1.584} - 2.684 \cdot x + 911.083$$

The outcomes of measurements and computations have been condensed into a table 5.

Table 5

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	15	20	25	30	35	40
Cross-sectional area:								
Actual, mm^2	910.975	939.012	972.922	1018.501	174.265	1138.719	1210.475	1288.314
Estimated, mm^2	911.083	938.212	973.41	1.019e3	1.074e3	1.138 e3	1.21 e3	1.289 e3
Relative error, %	0.012	0.085	0.05	0.07	0.014	0.05	0.055	0.045

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.218 \cdot x^{1.594} - 0.416 \cdot x + 299.166$$

The outcomes of measurements and computations have been condensed into a table 6.

Table 6

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	15	20	25	30	35	40
Perimeter:								
Actual, mm	299.149	303.674	309.152	316.522	325.549	335.997	347.645	360.297
Estimated, mm	299.166	303.547	309.229	316.635	325.573	335.908	347.539	360.388
Relative error, %	5.797e-3	0.042	0.025	0.036	7.298e-3	0.027	0.03	0.025

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.996	0.996

- Channel №10U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.287 \cdot x^{1.597} - 2.63 \cdot x + 1.11 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 7.

Table 7

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	15	20	25
Cross-sectional area:					
Actual, mm^2	1109.957	1135.882	1167.479	1210.329	1263.289
Estimated, mm^2	1.11 e3	1.135 e3	1.168 e3	1.211 e3	1.264 e3
Relative error, %	0.019	0.106	0.029	0.08	0.054

Continua of table 7

Displacement, mm	30	35	40	46
Cross-sectional area:				
Actual, mm^2	1325.147	1394.718	1470.910	1569.716
Estimated, mm^2	1.325 e3	1.394 e3	1.47 e3	1.571 e3
Relative error, %	9.1e-3	0.061	0.059	0.054

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.19 \cdot x^{1.606} - 0.391 \cdot x + 361.55$$

The outcomes of measurements and computations have been condensed into a table 8.

Table 8

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	15	20	25
Perimeter:					
Actual, mm	361.517	365.5	370.358	376.952	385.109
Estimated, mm	361.55	365.318	370.408	377.098	385.212

Relative error, %	9.004e-3	0.05	0.014	0.039	0.027

Continua of table 8

Displacement, mm	30	35	40	46
Perimeter:				
Actual, mm	394.646	405.385	417.159	432.446
Estimated, mm	394.629	405.258	417.027	432.573
Relative error, %	4.35e-3	0.031	0.032	0.029

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.995	0.995

- Channel №12U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.157 \cdot x^{1.616} - 2.457 \cdot x + 1.347 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 9.

Table 9

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40	52
Cross-sectional area:						
Actual, mm^2	1347.239	1371.924	1443.451	1555.369	1699.72	1905.283
Estimated, mm^2	1.347 e3	1.371 e3	1.445 e3	1.556 e3	1.698 e3	1.906 e3
Relative error, %	0.019	0.088	0.096	0.031	0.088	0.029

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.161 \cdot x^{1.624} - 0.342 \cdot x + 423.723$$

The outcomes of measurements and computations have been condensed into a table 10.

Table 10

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40	52
Perimeter:						
Actual, mm	423.686	427.235	437.527	453.654	474.49	504.223
Estimated, mm	423.723	427.064	437.723	453.724	474.28	504.302
Relative error, %	8.636e-3	0.04	0.045	0.015	0.044	0.016

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.995	0.995

- Channel №14U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.121 \cdot x^{1.62} - 2.549 \cdot x + 1.587 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 11.

Table 11
Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50	58
Cross-sectional area:							
Actual, mm²	1586.583	1609.993	1678.262	1786.255	1927.307	2094.749	2243.768
Estimated, mm²	1.587 e3	1.608 e3	1.680 e3	1.788 e3	1.926 e3	2.093 e3	2.245 e3
Relative error, %	0.027	0.108	0.082	0.07	0.045	0.077	0.052

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.149 \cdot x^{1.627} - 0.339 \cdot x + 486.283$$

The outcomes of measurements and computations have been condensed into a table 12.

Table 12
Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50	58
Perimeter:							
Actual, mm	486.224	489.429	498.783	513.596	532.970	556.005	576.534
Estimated, mm	486.283	489.194	498.967	513.765	532.853	555.787	576.692
Relative error, %	0.012	0.048	0.037	0.033	0.022	0.039	0.027

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.995	0.995

- Channel №16U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.085 \cdot x^{1.623} - 2.61 \cdot x + 1.837 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 13.

Table 13
Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50	64
Cross-sectional area:							
Actual, mm²	1836.125	1858.404	1923.692	2027.840	2165.247	2330.036	2596.673
Estimated, mm²	1.837 e3	1.856 e3	1.925 e3	2.03 e3	2.165 e3	2.328 e3	2.598 e3
Relative error, %	0.033	0.118	0.066	0.089	0.011	0.096	0.038

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.138 \cdot x^{1.631} - 0.332 \cdot x + 548.485$$

The outcomes of measurements and computations have been condensed into a table 14.

Table 14
Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50	64

Perimeter:							
Actual, mm	548.407	551.326	559.885	573.550	591.602	613.281	648.417
Estimated, mm	548.485	551.042	560.046	573.784	591.572	612.992	648.546
Relative error, %	0.014	0.051	0.029	0.041	0.00512	0.047	0.02

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

- Channel №18U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 1.03 \cdot x^{1.631} - 2.614 \cdot x + 2.099 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 15.

Table 15

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40	55	70
Cross-sectional area:							
Actual, mm²	2098.175	2119.476	2182.134	2282.746	2416.575	2668.353	2967.267
Estimated, mm²	2.099 e3	2.117 e3	2.183 e3	2.285 e3	2.417 e3	2.665 e3	2.969 e3
Relative error, %	0.038	0.123	0.045	0.092	0.015	0.108	0.043

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.126 \cdot x^{1.638} - 0.32 \cdot x + 611.045$$

The outcomes of measurements and computations have been condensed into a table 16.

Table 16

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40	55	70
Perimeter:							
Actual, mm	610.945	613.627	621.518	634.198	651.081	682.893	720.728
Estimated, mm	611.045	613.305	621.637	634.457	651.127	682.534	720.885
Relative error, %	0.016	0.052	0.019	0.041	0.007	0.053	0.022

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

4.2. The research and analysis alterations in the cross-sectional area and perimeter while displacement along the height of the channel

When shifting the saw along the wall (leg) of channel number 5U with height h, which is manufactured according to DSTU 3436-96 " Hot-rolled steel channels (Rolling products)" (Fig. 3) the

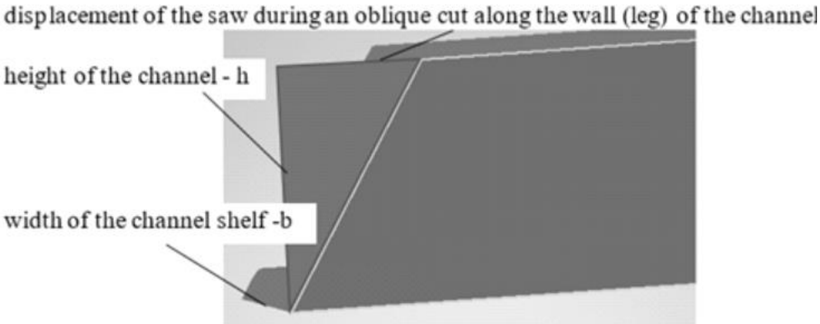


Figure 3: The scheme of the displacement of the saw during an oblique cut along the height of the channel

value of the cross-sectional area depending on the amount of displacement along the channel shelf can be described by the equation:

$$Pl(x) = 0.614 \cdot x^{1.604} - 1.314 \cdot x + 626.844$$

After estimating the values of the studied parameter according to the proposed dependence, a comparison of the areas of the sheared layer with the actual indicators was carried out (see Table 17).

Table 17

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	15	20	25
Cross-sectional area:					
Actual, mm^2	626.689	639.100	654.283	674.965	700.660
Estimated, mm^2	626.844	638.356	654.368	675.488	701.155
Relative error, %	0.025	0.116	0.013	0.078	0.071

Continua of table 17

Displacement, mm	30	35	40	45	50
Cross-sectional area:					
Actual, mm^2	730.839	764.971	802.554	843.124	886.272
Estimated, mm^2	730.98	764.67	801.996	842.769	886.831
Relative error, %	0.019	0.039	0.07	0.042	0.063

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.086 \cdot x^{1.618} - 0.186 \cdot x + 208.941.$$

The outcomes of measurements and computations have been condensed into a table 18.

Table 18

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	15	20	25
Perimeter:					
Actual, mm	208.918	210.770	213.038	216.130	219.977
Estimated, mm	208.941	210.662	213.049	216.206	220.049
Relative error, %	0.011	0.051	5.38e-3	0.035	0.033

Continua of table 18

Displacement, mm	30	35	40	45	50
Perimeter:					

Actual, mm	224.501	229.627	235.279	241.391	247.902
Estimated, mm	224.522	229.584	235.198	241.339	247.983
Relative error, %	9.539e-3	0.019	0.034	0.021	0.033

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.995	0.995

- Channel №6.5U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.466 \cdot x^{1.613} - 1.148 \cdot x + 763.042.$$

The outcomes of measurements and computations have been condensed into a table 19.

Table 19

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40
Cross-sectional area:					
Actual, mm^2	762.737	771.711	798.027	840.056	895.590
Estimated, mm^2	763.042	770.660	798.499	840.951	895.807
Relative error, %	0.04	0.136	0.059	0.107	0.024

Continua of table 19

Displacement, mm	45	50	55	60	65
Cross-sectional area:					
Actual, mm^2	927.687	962.294	999.150	1038.015	1078.673
Estimated, mm^2	927.452	961.736	998.553	1.038e3	1.079e3
Relative error, %	0.025	0.058	0.06	0.02	0.07

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.072 \cdot x^{1.623} - 0.178 \cdot x + 254.352$$

The outcomes of measurements and computations have been condensed into a table 20.

Table 20

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40
Perimeter:					
Actual, mm	254.304	255.750	259.994	266.780	275.762
Estimated, mm	254.352	255.585	260.067	266.921	275.797
Relative error, %	0.019	0.065	0.028	0.053	0.013

Continua of table 20

Displacement, mm	45	50	55	60	65
Perimeter:					
Actual, mm	280.960	286.570	292.551	298.864	305.475

Estimated, mm	280.924	286.483	292.457	298.831	305.594
Relative error, %	0.013	0.03	0.032	0.011	0.039

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.995

- Channel №8U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.37 \cdot x^{1.626} - 1.035 \cdot x + 911.461$$

The outcomes of measurements and computations have been condensed into a table 21.

Table 21

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40
Cross-sectional area:					
Actual, mm^2	910.975	918.065	939.012	972.922	1018.501
Estimated, mm^2	911.461	916.768	939.090	973.857	1.019e3
Relative error, %	0.053	0.141	8.329e-3	0.096	0.073

Continua of table 21

Displacement, mm	50	60	70	80
Cross-sectional area:				
Actual, mm^2	1074.265	1138.719	1210.475	1288.314
Estimated, mm^2	1.074 e3	1.138 e3	1.21 e3	1.289 e3
Relative error, %	9.835e-3	0.079	0.068	0.068

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.059 \cdot x^{1.635} - 0.167 \cdot x + 299.229$$

The outcomes of measurements and computations have been condensed into a table 22.

Table 22

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40
Perimeter:					
Actual, mm	299.149	300.334	303.835	309.506	317.138
Estimated, mm	299.229	300.122	303.846	309.659	317.260
Relative error, %	0.027	0.071	3.777e-3	0.049	0.039

Continua of table 22

Displacement, mm	50	60	60	65
Perimeter:				
Actual, mm	326.485	337.304	349.365	362.467

Estimated, mm	326.469	337.157	349.23	362.61
Relative error, %	4.953e-3	0.043	0.039	0.04

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

- Channel №10U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.313 \cdot x^{1.627} - 1.016 \cdot x + 1.111 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 23.

Table 23

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50
Cross-sectional area:						
Actual, mm²	1109.957	1115.493	1131.938	1158.829	1195.460	1240.970
Estimated, mm²	1.111e3	1.114e3	1.131e3	1.159e3	1.197e3	1.242e3
Relative error, %	0.074	0.145	0.048	0.057	0.097	0.069

Continua of table 23

Displacement, mm	60	70	80	90	100
Cross-sectional area:					
Actual, mm²	1294.421	1354.875	1421.438	1493.294	1569.716
Estimated, mm²	1.294e3	1.354e3	1.42e3	1.493e3	1.571e3
Relative error, %	4.579e-3	0.059	0.085	0.045	0.081

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.052 \cdot x^{1.635} - 0.17 \cdot x + 361.657$$

The outcomes of measurements and computations have been condensed into a table 24.

Table 24

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	10	20	30	40	50
Perimeter:						
Actual, mm	361.517	362.469	365.300	369.931	376.243	384.091
Estimated, mm	361.657	362.196	365.208	370.042	376.438	384.237
Relative error, %	0.039	0.075	0.025	0.03	0.052	0.038

Continua of table 24

Displacement, mm	60	70	80	90	100
Perimeter:					
Actual, mm	393.317	403.761	415.271	427.709	440.951

Estimated, mm	393.328	403.627	415.068	427.596	441.165
Relative error, %	2.765e-3	0.033	0.049	0.027	0.048

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

- Channel №12U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.293 \cdot x^{1.62} - 1.044 \cdot x + 1.348 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 25.

Table 25

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	20	40	60	80	100	120
Cross-sectional area:							
Actual, mm^2	1347.239	1365.822	1420.114	1506.258	1619.179	1753.712	1905.283
Estimated, mm^2	1.348e3	1.364e3	1.421e3	1.507e3	1.619e3	1.752e3	1.906e3
Relative error, %	0.03	0.113	0.077	0.079	0.033	0.087	0.049

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.048 \cdot x^{1.627} - 0.173 \cdot x + 423.754$$

The outcomes of measurements and computations have been condensed into a table 26.

Table 26

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	20	40	60	80	100	120
Perimeter:							
Actual, mm	423.686	426.859	436.135	450.867	470.203	493.272	519.301
Estimated, mm	423.754	426.598	436.317	451.068	470.115	493.015	519.456
Relative error, %	0.016	0.061	0.042	0.044	0.019	0.052	0.03

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

- Channel №14U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.158 \cdot x^{1.705} - 0.498 \cdot x + 1.586 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 27.

Table 27

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	20	40	60
Cross-sectional area:				
Actual, mm^2	1586.583	1602.691	1650.072	1726.151
Estimated, mm^2	1.586e3	1.603e3	1.652e3	1.727e3
Relative error, %	0.017	9.611e-3	0.103	0.043

Continua of table 27

Displacement, mm	80	100	120	140
Cross-sectional area:				
Actual, mm^2	1827.349	1949.758	2071.504	2243.768
Estimated, mm^2	1.825e3	1.944e3	2.082e3	2.239e3
Relative error, %	0.136	0.307	0.522	0.194

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.026 \cdot x^{1.712} - 0.081 \cdot x + 486.174$$

The outcomes of measurements and computations have been condensed into a table 28.

Table 28

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	20	40	60
Perimeter:				
Actual, mm	486.224	488.955	496.993	509.907
Estimated, mm	486.174	488.937	497.281	510.028
Relative error, %	0.01	3.78e-3	0.058	0.024

Continua of table 28

Displacement, mm	80	100	120	140
Perimeter:				
Actual, mm	527.100	547.919	568.646	598.008
Estimated, mm	526.674	546.904	570.491	597.263
Relative error, %	0.081	0.185	0.324	0.125

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.979	0.979

- Channel №16U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.244 \cdot x^{1.624} - 1.043 \cdot x + 1.837 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 29.

Table 29

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	25	50	75
Cross-sectional area:				
Actual, mm^2	1836.125	1858.404	1923.692	2027.840
Estimated, mm^2	1.837e3	1.856e3	1.925e3	2.03e3
Relative error, %	0.034	0.119	0.064	0.089

Continua of table 29

Displacement, mm	100	125	150	160
Cross-sectional area:				
Actual, mm^2	2165.247	2330.036	2516.836	2596.673
Estimated, mm^2	2.165e3	2.328e3	2.516e3	2.598e3
Relative error, %	8.072e-3	0.088	0.027	0.056

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.04 \cdot x^{1.63} - 0.171 \cdot x + 548.51$$

The outcomes of measurements and computations have been condensed into a table 30.

Table 30

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	25	50	75
Perimeter:				
Actual, mm	548.407	552.143	563.095	580.579
Estimated, mm	548.51	551.776	563.298	580.878
Relative error, %	0.019	0.066	0.036	0.052

Continua of table 30

Displacement, mm	100	125	150	160
Perimeter:				
Actual, mm	603.669	631.392	662.856	676.314
Estimated, mm	603.641	631.054	662.745	676.553
Relative error, %	4.578e-3	0.053	0.017	0.035

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.995	0.995

- Channel №18U

A proposed function for approximating the cross-sectional area is presented:

$$Pl(x) = 0.231 \cdot x^{1.624} - 1.064 \cdot x + 2.099 \cdot 10^3$$

The outcomes of measurements and computations have been condensed into a table 31.

Table 31

Comparative data of cross-sectional areas for straight and oblique cuts

Displacement, mm	0	25	50	75
Cross-sectional area:				
Actual, mm^2	2098.175	2118.315	2177.619	2273.022

Estimated, mm^2	2.099e3	2.115e3	2.178e3	2.275e3
Relative error, %	0.044	0.134	0.036	0.101

Continua of table 31

Displacement, mm	100	125	150	180
Cross-sectional area:				
Actual, mm^2	2400.225	2554.482	2731.211	2967.267
Estimated, mm^2	2.401e3	2.553e3	2.729e3	2.969e3
Relative error, %	0.041	0.055	0.088	0.056

A proposed function for approximating the cross-sectional perimeter is presented:

$$Per(x) = 0.037 \cdot x^{1.63} - 0.172 \cdot x + 611.096$$

The outcomes of measurements and computations have been condensed into a table 32.

Table 32

Comparative data of the cross-sectional perimeter for straight and oblique cuts

Displacement, mm	0	25	50	75
Perimeter:				
Actual, mm	610.945	614.275	624.082	639.868
Estimated, mm	611.096	613.812	624.209	640.242
Relative error, %	0.025	0.075	0.02	0.059

Continua of table 32

Displacement, mm	100	125	150	180
Perimeter:				
Actual, mm	660.931	686.498	715.817	755.021
Estimated, mm	661.095	686.271	715.422	755.290
Relative error, %	0.025	0.033	0.055	0.036

The coefficients of determination R^2 were calculated for the proposed approximating functions using a discrete set of input data:

	when using mathematical dependence for:	
	cross-sectional area	cross-section perimeter
R^2	0.994	0.994

5. Conclusions

In the process of cutting a part of a complex geometric profile (channel) at different angles, it has been observed that the perimeter and cross-sectional area do not change proportionally to the angle of the cut. This applies to both angular cuts made along the height and width of the profile.

For each standard size of the channel, we defined mathematical construction that explains how the perimeter and cross-sectional area of the profile change based on the displacement of the metal-cutting tool relative to the base points in the normal section. Studies have shown that the best way to present these mathematical models is through a non-linear regression of the general type.

The accuracy of the mathematical models developed was confirmed by calculating the coefficient of determination R^2. The values obtained ranged from 0.994 to 0.997, with only one case showing 0.979. These results indicate that the proposed mathematical models accurately depict the measurement results obtained from both mathematics analysis and 3D modeling.

The proposed mathematical models provide effective design of welded joints of metal structures. Their use in specialized modules of intelligent and information systems can solve problematic moments in the organization, planning and execution of mechanical processing and welding operations.

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