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PHYSICAL MODELLING OF THE INFLUENCE OF TECHNOLOGICAL PARAMETERS OF THE HOT ROLLING PROCESS ON THE TRANSVERSE FLOW OF MATERIAL

The article discusses the impact of technological parameters on the degree of material widening in the hot rolling process. Physical simulation studies were conducted for S235JR steel and Grade 2 titanium. The result of the experiments was the determination of dependencies that allow the degree of material widening in the hot rolling process to be calculated. A heating furnace was used for the physical modelling studies to heat the samples in the temperature range of 750 to 1200°C, and a single-stand reversing duo/quarto rolling mill equipped with small-size sample feeding equipment (Fig. 1). The study results indicate considerable discrepancies in the calculations of expansion magnitude based on the widely applied formulas found in rolling literature. The computed values substantially deviate from those obtained through physical simulation.

Keywords: Steel; titanium; thermal conductivity coefficient; widening; temperature; rolling

1. Introduction

During the rolling process, the material simultaneously elongates and widens. Designing the rolling technology requires not only calculating the forces involved in the plastic deformation of the material but also calculating the degree of widening of the product during rolling. The currently applied equations for calculating the material expansion magnitude consider a greater or lesser number of technological factors but disregard their physical properties (including thermal conductivity) and are primarily tailored to steel products. There is a lack of literature data describing the influence of technological parameters on the expansion of titanium during the hot rolling process [1-5].

Calculations of the widening of the rolled strip become particularly important when designing rolling technology in passes. Knowledge of the degree of widening is essential for determining material flow in the pass to ensure proper filling during rolling. The values of these quantities are influenced by such rolling process parameters as the degree of reduction, the shape factor of the cross-section, the geometric factor of the rolling groove, the temperature of the deformed strip, the rolling speed, and the chemical composition of the material.

Based on the current analysis of knowledge about the issue of material flow in the rolling process [4,5,8,9], it can be stated that the search for a solution to the problem is performed using empirical methods, leading to the development of mathematical dependencies that take into account the basic technological factors affecting material flow in the rolling process, including the degree of reduction, deformation speed, temperature, roll diameter, strip shape factor, geometric factor of the rolling groove, and friction coefficient. Classic determination of dependencies describing material flow in the width direction is usually conducted for a specific material grade (primarily for steel) and technological process, which largely results from the inherent properties of the rolled strip [6,7,10-13]. This approach to the issue has led to the creation of many formulas enabling the calculation of widening, which is often complicated to apply in practice. All developed dependencies have a very narrow range of applications, which are often empirically verified by technologists to identify the dependency that best describes real processes.

The conducted research and analysis of the current state of the issue showed that building a model of transverse material flow in the hot rolling process requires incorporating all factors influencing this process, including the thermal conductivity coefficient.

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2. Material and methodology

The material flow study in the direction transverse to the rolling direction was conducted at the Łukasiewicz Research Network – Upper Silesian Institute of Technology, in module B of the LPS line for semi-industrial simulation of hot rolling processes. Materials with different thermal conductivity coefficients were selected for the study. The thermal conductivity coefficients of the chosen materials, depending on the hot plastic working temperature, were compiled based on literature data [6] in TABLE 1. The chemical compositions of the tested materials are shown in TABLES 2 and 3. The research input consisted of certified flat bar materials, purchased and subsequently cut into samples with dimensions specified in TABLE 4.

All samples were milled and ground after cutting to ensure that the sample surfaces were free of delaminations and cracks. A total of 54 samples were prepared.

Fig. 1. Single-pass hot rolling of small-sized samples in the LPS/B line

3. Research programme

The research program for material flow in the direction transverse to the rolling direction was developed considering the influence of:

TABLE 1

Thermal Conductivity of materials

No.	Material type	Temperature, °C	Thermal Conductivity, W/mK
1	Titanium Grade 2	750 ÷ 900	18,0
2	Steel S235JR	850 ÷ 900	26,8

TABLE 2

Chemical composition of Titanium Grade 2

Element Content, wt.%					
N	Fe	O	H	C	Ti
0,028	0,17	0,17	0,001	0,03	balance

- thermal conductivity coefficient: by using samples from different materials (carbon steel, titanium),
- the shape factor of the strip: by using samples with widths of 20, 40, and 60 mm, while maintaining a constant height of 20 mm,
- roll diameter: by using three rolls with working diameters of 130, 407, and 550 mm,
- temperature: by conducting studies within the temperature range of hot plastic working, selected appropriately for the rolled material; each material was rolled at three different temperatures within the specified range,
- degree of deformation: by using reductions of 10%, 20%, and 30%.

Due to the large number of samples necessary to conduct the full scope of the experiment, which significantly affects the cost of the research, it was decided to develop a research program involving the selection of representative deformation schemes for the material in the rolling process. This program considers the influence of the thermal conductivity coefficient, shape factor of the cross-section, degree of reduction, temperature, and roll diameter.

The studies of material flow in the direction transverse to the rolling direction were conducted using module B of the LPS line according to the program presented in TABLE 5.

TABLE 3

Chemical composition of Steel S235JR

Element Content, wt.%										
C	Mn	Si	P	S	Cr	Ni	V	Mo	Cu	Al
0,140	0,770	0,188	0,014	0,009	0,030	0,020	0,0020	0,002	0,020	0,040

TABLE 4

Sample specifications

No.	Material Type	Number of Samples	Thickness, mm	Width, mm	Length, mm
1	Titanium Grade 2	9	20	20	200
2	Titanium Grade 2	9	20	30	200
3	Titanium Grade 2	9	20	60	200
4	Steel S235JR	9	20	20	200
5	Steel S235JR	9	20	30	200
6	Steel S235JR	9	20	60	200

TABLE 5

Research Program to Determine the Influence of Technological Parameters of Hot Rolling Process on Transverse Material Flow under LPS/B Line Conditions (1A/550 – sample numbers)

Roll diameter – 550 mm in duo arrangement, rolling speed – 0.2 m/s, friction coefficient – 0.35							
Temperature	**Reduction**	**Steel S235JR**			**Titanium Grade 2**		
		20×20×200	**20×30×200**	**20×60×200**	**20×20×200**	**20×30×200**	**20×60×200**
°C	**%**	**mm**	**mm**	**mm**	**Mm**	**mm**	**mm**
750	**10**				1T/550		
	20						2T/550
	30					3T/550	
850	**10**						4T/550
	20					5T/550	
	30				6T/550		
900	**10**	1A/550				7T/550	
	20			2A/550	8T/550		
	30		3A/550				9T/550
1050	**10**			4A/550			
	20		5A/550				
	30	6A/550					
1200	**10**		7A/550				
	20	8A/550					
	30			9A/550			
Roll diameter – 407 mm in duo arrangement, rolling speed – 0.2 m/s, friction coefficient – 0.35							
750	**10**					1T/407	
	20				2T/407		
	30						3T/407
850	**10**				4T/407		
	20						5T/407
	30					6T/407	
900	**10**		1A/407				7T/407
	20	2A/407				8T/407	
	30			3A/407	9T/407		
1050	**10**	4A/407					
	20			5A/407			
	30		6A/407				
1200	**10**			7A/407			
	20		8A/407				
	30	9A/407					
Roll diameter – 130 mm in duo arrangement, rolling speed – 0.2 m/s, friction coefficient – 0.35							
750	**10**						1T/130
	20					2T/130	
	30				3T/130		
850	**10**					4T/130	
	20				5T/130		
	30						6T/130
900	**10**			1A/130	7T/130		
	20		2A/130				8T/130
	30	3A/130				9T/130	
1050	**10**		4A/130				
	20	5A/130					
	30			6A/130			
1200	**10**	7A/130					
	20			8A/130			
	30		9A/130				

4. Research results

The results of the measurements of height, width, and length of the samples after hot rolling in module B of the LPS are presented in TABLES 6 to 8. The relative reduction for all tested samples was calculated, and the sample temperatures during rolling were recorded. The reduction was calculated based on the measurements of sample height before and after rolling.

Visual analysis of the material surface condition did not reveal any cracks.

The absolute widening Δb as a function of the cross-section shape factor $\delta\omega$, for reductions of 10% and 30%, with rolls of 550 mm diameter, is presented in the form of graphical from in Figs. 2 and 3.

The widening as a function of absolute reduction Δh depending on the roll diameter is shown in Figs. 6 and 7, and as a function of absolute reduction Δh depending on the rolled material grade in Figs. 8 and 9.

Based on the characteristics and tabulated data from the physical modelling, the following dependencies can be observed:

- as the hot plastic working temperature increases, the value of the absolute widening Δb increases.
- samples with dimensions of 20×30 mm deformed with reductions of 10% and 20% achieve a greater widening value, the widening value significantly increases in the case of rolling titanium, which has the lowest thermal conductivity coefficient among the tested materials (Figs. 2 and 3).
- as the cross-section shape factor increases, the widening value decreases (Figs. 4 and 5).
- as the roll diameter increases, the widening value increases (Figs. 6 and 7).
- as the reduction increases, the flow in the width direction increases (Figs. 8 to 9).
- as the material's thermal conductivity coefficient increases, the flow in the width direction decreases.

The highest widening values for the tested materials are obtained during the rolling of the material with the lowest thermal conductivity coefficient, i.e., titanium.

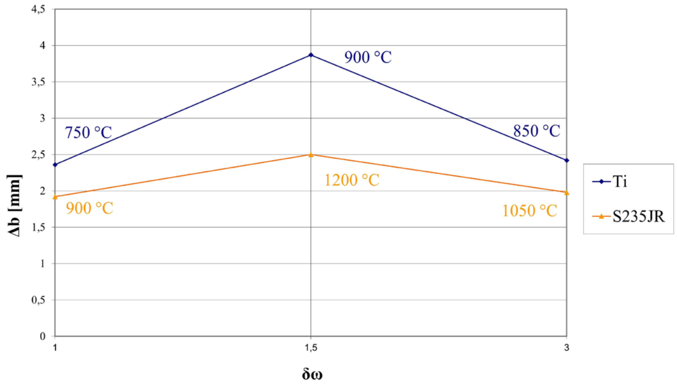


Fig. 2. Absolute expansion Δb as a function of the shape coefficient $\delta\omega$ for samples rolled with a 10% reduction in a duo arrangement with work rolls of 550 mm diameter

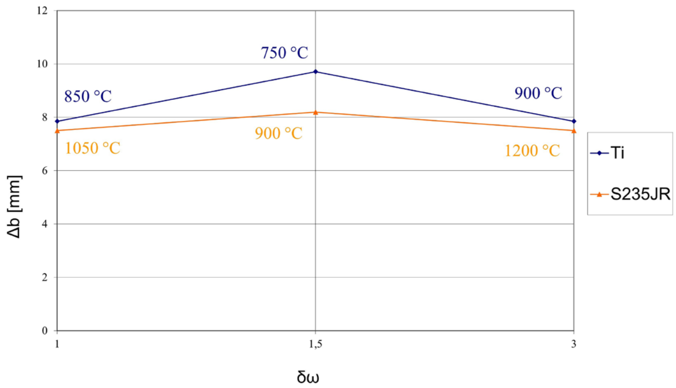


Fig. 3. Absolute expansion Δb as a function of the shape coefficient $\delta\omega$ for samples rolled with a 30% reduction in a duo arrangement with work rolls of 550 mm diameter

TABLE 6

Research results from rolling in the duo 500 mm arrangement (T – titanium Grade 2, A – steel S235JR)

No.	Sample / batch identification	Sample dimensions			Simple dimensions after rolling			Heating time	Rolling temperature	Draft
		Height before	Width before	Length before	Height after	Width after	Length after			
		mm	mm	mm	mm	mm	mm	min	°C	%
1	1T/550	20,08	20,13	200,00	17,88	22,49	211,00	32	730	10,96
2	2T/550	20,09	60,06	200,00	16,00	64,41	240,00	36	732	20,36
3	3T/550	20,08	29,99	200,00	13,82	39,70	233,00	50	733	31,18
4	4T/550	20,08	60,04	199,50	17,96	62,46	225,00	50	822	10,56
5	5T/550	20,08	29,86	199,90	15,79	36,96	223,00	51	830	21,36
6	6T/550	20,08	20,08	200,00	13,46	27,93	237,00	55	815	32,97
7	7T/550	20,05	30,10	200,00	17,89	33,97	217,00	53	880	10,77
8	8T/550	20,08	20,10	200,00	15,83	25,54	227,00	60	889	21,17
9	9T/550	20,00	60,04	200,00	13,83	70,50	264,00	61	890	30,85
10	1A/550	20,00	19,97	199,50	17,84	21,89	216,00	47	880	10,80
11	2A/550	20,04	60,02	200,00	16,10	63,65	245,00	50	890	19,66
12	3A/550	20,05	29,99	200,00	13,90	38,18	240,00	53	875	30,67
13	4A/550	20,08	60,04	199,00	17,68	62,02	228,00	40	1030	11,95
14	5A/550	20,00	30,00	199,00	15,76	35,39	233,50	43	1031	21,20
15	6A/550	20,00	19,95	199,00	13,54	27,45	230,00	47	1025	32,30
16	7A/550	20,01	30,00	199,00	17,81	32,50	223,00	45	1180	10,99
17	8A/550	19,95	20,00	199,00	15,85	25,26	224,00	50	1179	20,55
18	9A/550	20,03	60,05	199,00	14,07	68,15	274,00	52	1182	29,76

TABLE 7

Results of rolling in a duo arrangement with 407 mm (T – titanium Grade 2, A – steel S235JR)

No.	Sample / batch identification	Sample dimensions			Simple dimensions after rolling			Heating time	Rolling temperature	Draft
		Height before	Width before	Length before	Height after	Width after	Length after			
		mm	mm	mm	mm	mm	mm	min	°C	%
1	1T/407	20,08	30,06	200,00	17,79	31,40	218,00	40	731	11,40
2	2T/407	20,08	20,08	200,00	15,86	23,78	222,50	42	733	21,02
3	3T/407	20,03	59,93	200,00	14,18	64,71	265,00	44	732	29,21
4	4T/407	19,85	20,05	200,00	17,69	21,54	214,50	43	823	10,88
5	5T/407	20,06	60,04	200,00	16,11	62,86	241,00	45	831	19,69
6	6T/407	20,05	29,86	199,00	13,91	36,49	246,00	48	816	30,62
7	7T/407	20,05	60,04	199,00	17,76	62,12	224,00	50	882	11,42
8	8T/407	20,05	29,97	199,00	15,59	35,48	226,00	52	886	22,24
9	9T/407	20,09	20,11	199,00	13,70	28,97	232,00	54	891	31,81
10	1A/407	20,01	30,01	199,00	17,83	31,30	218,00	52	881	10,89
11	2A/407	20,03	20,00	199,00	15,87	23,36	224,00	55	889	20,77
12	3A/407	20,03	60,03	199,00	14,13	64,35	264,00	57	890	29,46
13	4A/407	20,03	20,00	199,00	17,86	21,45	216,00	48	1031	10,83
14	5A/407	20,03	60,01	199,00	16,03	62,57	241,00	50	132	19,97
15	6A/407	20,02	30,01	199,00	13,97	35,26	249,00	52	1033	30,22
16	7A/407	20,02	60,00	199,00	17,90	61,09	226,00	47	1181	10,59
17	8A/407	20,02	29,97	199,00	15,88	33,08	234,00	49	1180	20,68
18	9A/407	20,02	19,93	199,00	13,67	24,88	239,00	53	1188	31,72

TABLE 8

Results of rolling in a quarter arrangement for 130 mm work rolls (T – titanium Grade 2, A – steel S235JR)

No.	Sample / batch identification	Sample dimensions			Simple dimensions after rolling			Heating time	Rolling temperature	Draft
		Height before	Width before	Length before	Height after	Width after	Length after			
		mm	mm	mm	mm	mm	mm	min	°C	%
1	1T/130	20,07	60,04	199,95	18,06	60,66	223,00	42	729	10,01
2	2T/130	20,01	30,02	199,95	15,94	31,87	245,00	44	732	20,34
3	3T/130	20,05	20,06	199,95	13,89	23,86	—	46	732	30,72
4	4T/130	20,08	29,89	199,95	17,81	30,75	221,00	41	823	11,30
5	5T/130	20,08	20,05	199,95	15,68	22,11	244,00	43	831	21,91
6	6T/130	20,00	60,03	199,95	14,20	63,02	—	45	840	29,00
7	7T/130	20,01	20,10	200,00	17,95	21,21	221,00	48	881	10,29
8	8T/130	20,00	59,98	199,95	15,87	62,34	—	50	888	20,65
9	9T/130	20,02	30,00	199,95	13,79	36,06	—	52	889	31,12
10	1A/130	20,02	60,00	199,95	17,96	60,44	—	55	883	10,29
11	2A/130	20,01	29,98	199,95	15,88	31,66	246,00	57	889	20,64
12	3A/130	20,02	19,98	199,95	13,89	23,25	259,00	59	876	30,62
13	4A/130	20,02	30,00	199,95	17,98	30,67	222,00	50	1040	10,19
14	5A/130	20,05	19,95	199,95	15,88	21,88	241,00	53	1041	20,80
15	6A/130	20,02	60,04	199,95	13,63	61,83	—	55	1039	31,92
16	7A/130	20,00	20,00	199,00	17,92	20,52	223,50	55	1179	10,40
17	8A/130	20,05	60,05	199,95	15,74	60,54	—	57	1179	21,50
18	9A/130	20,00	30,00	199,00	13,67	33,07	269,00	60	1180	31,65

Impact of thermal conductivity on material flow: The study results demonstrated the influence of thermal conductivity on material flow in the width direction. Materials with a low thermal conductivity coefficient (11.4 W/mK for grade 2 titanium) exhibit greater transverse flow during rolling compared to materials with a thermal conductivity coefficient of 26.8 W/mK (carbon steel). The physical cause of this phenomenon is the very rapid cooling of the surface layers of the heated material (for titanium, 750 ÷ 900°C) upon contact with the roll surface (temperature 20 ÷ 80°C), which causes immediate cooling of the surface layers of the deformed material, resulting in intense transverse flow perpendicular to the rolling direction.

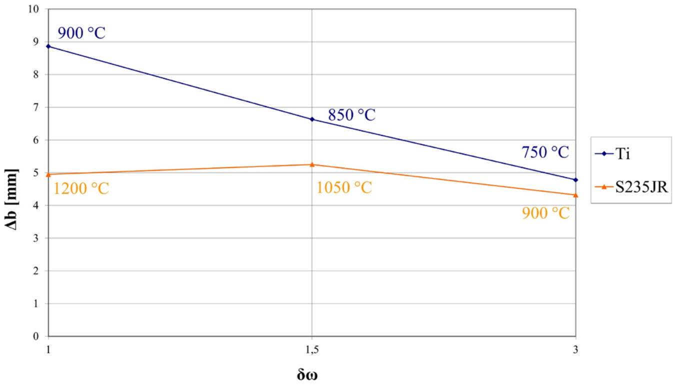


Fig. 4. Absolute expansion Δb as a function of the shape coefficient $\delta\omega$ for samples rolled with a 30% reduction in a duo arrangement with work rolls of 407 mm diameter

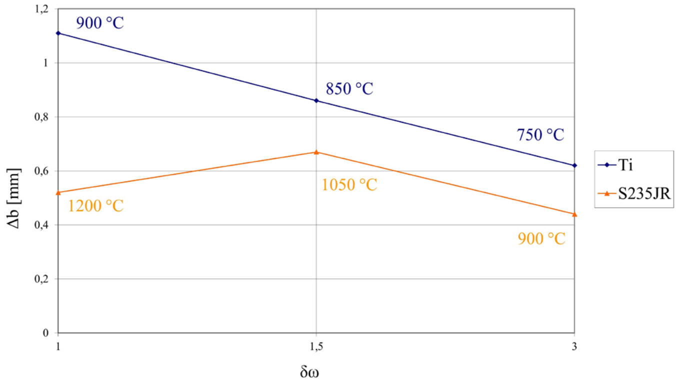


Fig. 5. Absolute expansion Δb as a function of the shape coefficient $\delta\omega$ for samples rolled with a 10% reduction in a quarter arrangement with work rolls of 130 mm diameter

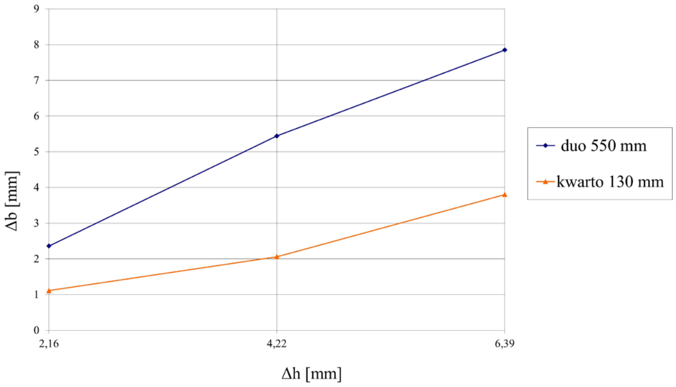


Fig. 6. Absolute expansion Δb as a function of absolute reduction Δh depending on the roll diameter for samples sized 20×20 mm made of titanium

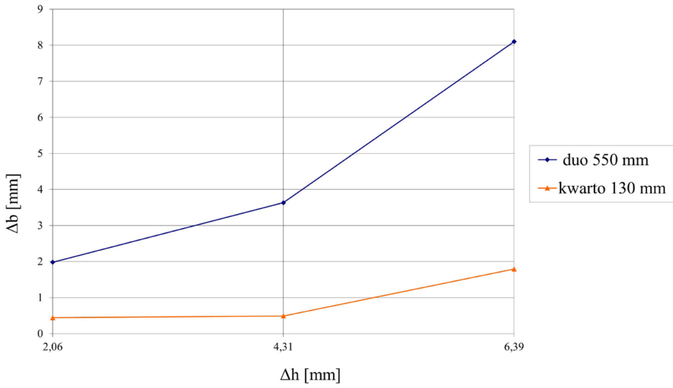


Fig. 7. Absolute expansion Δb as a function of absolute reduction Δh depending on the roll diameter for samples sized 20×60 mm made of S235JR steel

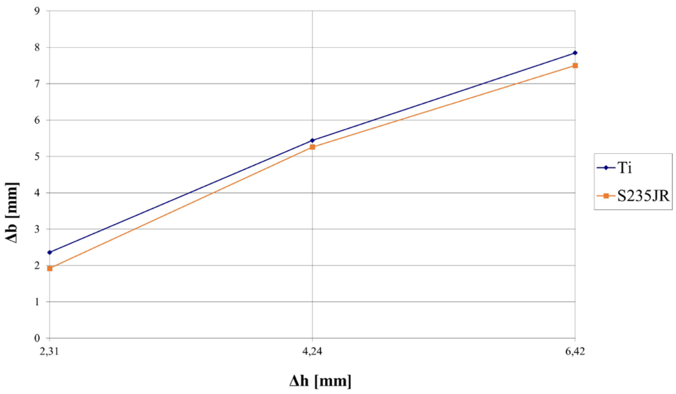


Fig. 8. Absolute expansion Δb as a function of absolute reduction Δh depending on the material type for samples sized 20×20 mm rolled in a duo arrangement with rolls of diameter 550 mm

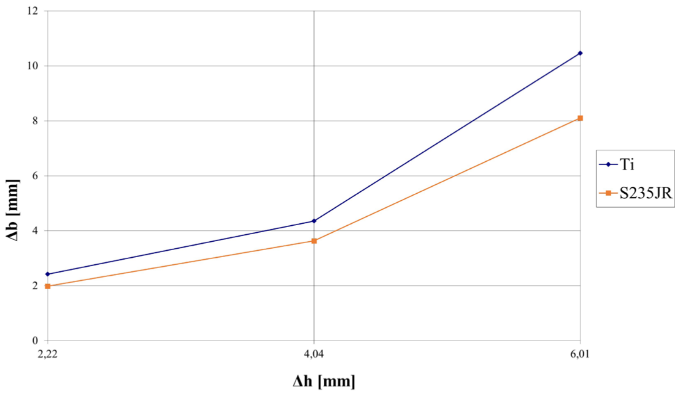


Fig. 9. Absolute expansion Δb as a function of absolute reduction Δh depending on the type of material for samples with dimensions of 20×60 mm rolled in a duo arrangement with rolls of 550 mm diameter

5. Analysis of results based on existing formulas for determining widening in the rolling process

The widening values obtained during the conducted studies were compared with the values calculated according to formulas known from the rolling theory. The most commonly used formulas in practical rolling operations were selected for calculations (Siebla, Bachtinov, Wusatowski, Tafel-Sedlaczek, and Celikov formulas).

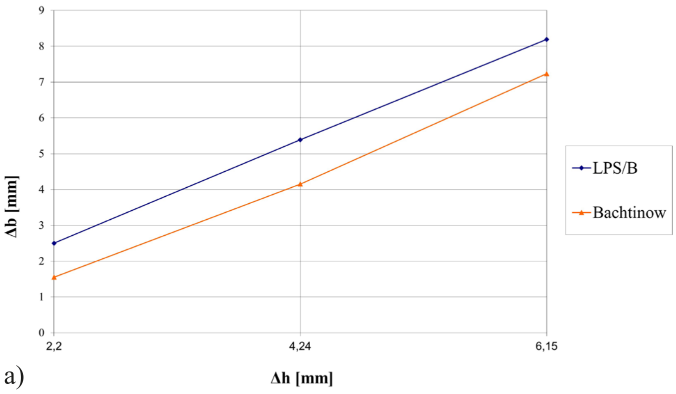
Existing formulas for determining free widening, which is not constrained by the side walls of the groove, allow for the calculation of only approximate widening values in the rolling process, without considering the thermal conductivity coefficient.

Although the applied formulas account for the basic factors influencing the transverse flow of material during rolling, such as absolute reduction, roll diameter, rolling temperature, and friction coefficient, the calculated values differ from the measured values (Fig. 10). Among the formulas used for calculations, the best results were obtained with the Bachtinov formula (1). The values calculated using this formula are the closest to the measured values.

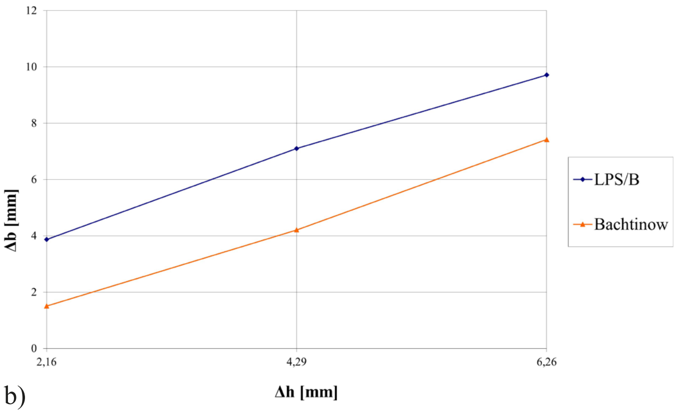
$$\Delta b = 1{,}15\frac{\Delta h}{2h_0}\left(\sqrt{R\Delta h - \frac{\Delta h}{2\mu}}\right) \tag{1}$$

where:

h_o – the height of the material before rolling,
R – radius of the working roll,
Δh – absolute reduction,
μ – friction coefficient.



a)



b)

Fig. 10. Absolute expansion Δb as a function of absolute reduction Δh for 20×30 samples rolled in a duo arrangement with rolls of 550 mm diameter: a) Steel 235JR, b) Titanium Grade 2

6. Conclusions

Based on the results of physical simulations performed using the method of hot rolling on a semi-industrial scale, the following conclusions can be formulated:

- Inadequacies of current calculation methods: The current dependencies used to calculate the material spread account for various technological factors such as the degree of reduction, roll diameter, shape factor of the strip, friction coefficient, and others. However, they overlook the physical properties of the material.
- Calculations of spread according to currently used formulas often yield results that significantly differ from actual values. This discrepancy arises because these formulas were developed empirically primarily for non-alloy steels.
- Need for further research: The developed research scope requires adjustments through the application of new materials with higher thermal conductivity coefficients in physical simulations and an increase in the number of samples to conduct a comprehensive experiment. This would allow for an expanded analysis of the influence of fundamental factors on material flow in the width direction and the development of a mathematical model of the influence of the material's thermal conductivity coefficient on transverse flow in the width direction during hot rolling.

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