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APPLICATION OF TEMPERATURE ANALYSIS TO ACCOUNT FOR THE EFFECT OF SHEET THICKNESS ON ROLLING FORCE

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Abstract. The relationship between the rolling force and the initial thickness of the Al-Mg-Li sheet preform for thicknesses of 1.8 mm and 4.8 mm was shown for cold rolling pre-quenched and artificial aging. Samples with a thickness of 7.3 mm were obtained by hot rolling with cooling from the deformation temperature. Thermoanalytical support of the rolling process is carried out by the method of temperature analysis based on isothermal discrete scanning (IDS) data. It gives the connection of effort with internal temperature distributions, which have general patterns of properties, regardless of the complexity of the structure and composition of the material. The presence of periodicity and steady-state temperatures after IDS makes it possible to partition the results of the temperature scanning of the samples into sections. As a result, it is possible to improve the accuracy of estimating the effect of the initial thickness of the workpiece on the force for each of the passes during cold rolling, without correction for the thermal or technological past.

Keywords: Al-Mg-Li sheet, cold rolling, temperature analysis

1. Introduction

During developing and introducing into production the technology for rolling sheets of the required thickness, thermal analysis (TA) methods have been applied. The heating rate is selected according to the registered thermal effects, for example, a thermoanalytical device (thermograph) with software control is used for this. The use of DTA (differential thermal analysis) allows solving a number of problems, such as determining the temperature and heat of phase transformations, determining the heat capacity of substances, determining the content of impurities in the substance, and determining the kinetic parameters of the chemical reaction.

However, like all experimental methods, thermal methods are not free of some limitations. The rate of change in temperature plays a significant role in the value of the phase transformation parameters. Sometimes with the help of rapid heating it is possible to melt the sample before its decay, while with slow heating the sample decomposes before melting. To approach equilibrium conditions, it is necessary to heat as slowly as possible. At low heating rates, it is possible to obtain signals on which the processes occurring in the sample are clearly separated, and, the lower the speed, the easier it is to divide them, in DTA, the control possibilities are limited here. During IDS (isothermal discrete scanning), the temperature and time can be any, and the speed is raised abruptly. Further, the temperature analysis (TmA) connects the description of transition structures and changes in the properties of substances with joints of temperature intervals [1]. The choice of the IDS method in the study is due to

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the fact that it can be used to obtain internal distributions of almost any material property, regardless of the complexity of the structure of the sample.

Thus, DTA method gives the heat values for the formation and decomposition of chemical compounds in the sample, and the IDS method gives the temperature distribution in the sample volume. The relationship between DTA and IDS methods is provided by meeting the isotemperature requirements for each heating and changing the samples so that the previous temperature changes can be cut off from subsequent changes at higher temperatures. As a result, they do not overlap. This provides a real distribution of temperature changes in the volume of samples and allows a sharp increase in the accuracy of determining the characteristic temperatures of single phases, chemical compounds and other parts of the material.

Investigation of the connection between mechanical impacts requires the inclusion of two discrete series [2]. The discrete series (T_π) in the given intervals reflects the process of energy absorption by the crystal lattice, is strictly observed in the temperature periods, and is used to divide the obtained data into regions for analysis. The discrete series (T_σ) in the indicated intervals shows the changes in the volume of the sample as a reaction of the mechanical impact:

(T_π) 171.5; 514.5; 857.5; 1200.5; 1543.5; …°C;

(T_σ) 0; 343; 686; 1029; …°C. (1)

IDS reflects the dynamics of modifications of structures in places of thermal effects and a change in density as the distribution of phases in the volume of the sample, which depend on temperature and external force. Previously, the utility of complex analysis using DTA and IDS methods was shown. They actually work as independent elements of one measuring system [3, 4].

The purpose of the article is to investigate the relationship between the rolling force and the initial thickness of Al-Mg-Li sheets. Samples with a thickness of 1.8 mm and 4.8 mm were obtained by cold rolling, passed quenching and artificial aging. Sheet samples with a thickness of 7.3 mm thickness were obtained by hot rolling with cooling from the temperature of hot deformation [8 – 13]. All samples are rolled on a KVARTO K220-75/300 laboratory mill with an electronic force measuring system with piezoelectric sensors glued to the stand of the stand. The IDS method was implemented in a simplified version, in order to take into account the influence of time, each sample was heated to a certain temperature before cold rolling and kept in the furnace for one, two or three minutes.

2. Determination of the correspondence between the periodicity of plastic deformation and the periodic grid of stationary temperatures

Classical concepts of plastic deformation are based on the fact that in the process of increasing the degree of deformation, dislocation defects accumulate. The greater the degree of plastic deformation, the more defects must contain a deformable crystal and, consequently, more elastic energy. However, there is an analogy between the process of energy absorption by the crystal lattice during plastic deformation and the process of metal heating. In either case, there is a critical value of the energy. In the first case, this distortion of the crystal lattice to a pseudocrystalline value in local volumes, and in the second case, a change in the heat content of the metal due to the absorption of additional energy by the crystal lattice [5, 14 – 16].

During rolling, the directional action of the deforming forces causes a rotation of the grains and their crystallographic axes along the direction of maximum deformation in the polycrystalline body. It is precisely the rotations of the grains and their crystallographic axes with rotational plasticity that are accompanied by a change in the symmetry of the order

parameter. They are associated with cardinal structural transformations, which reduce the critical level of elastic energy absorbed by the crystal lattice [6, 17 – 20].

Defining a change in the symmetry of the order parameter, and knowing the symmetry of the original structure for phase transitions of the second kind, one can find changes in the symmetry of the crystals during phase transitions associated with structural instability. A measure of the change in the symmetry of the order parameter is the measure of the stability of the system Δ_i and the values of the generalized "golden" proportion represented in the form of discrete sequence:

$\Delta_i = 0.618; 0.465; 0.380; 0.324; 0.285; 0.255; 0.232; 0.213.$ (2)

Such a change in the symmetry is localized at the appropriate temperatures and correlates to the second discrete series (1), which must agree with another discrete series of gold sections. It is to be developed, since the increase in grain size during IDS is quite short-term and refers to individual phases, and the others are not yet activated. Increasing the temperature causes the reverse process of reducing the grain size and causes a change in the rolling forces relative to the temperature of IDS [21].

3. Results of field research

The first investigated cold-rolled Al-Li-Mg sheet with a thickness 1.8 mm. From it preliminary samples were cut with a width of 30 mm and a length of 50 mm in an amount of 28 pieces for subsequent cold rolling on a laboratory rolling mill KVARTO K220-75 / 300. Before rolling, each sample was heated to a certain temperature by IMD method and stored in a thermograph for one minute. Each sample after individual heating according to the mode of IDS method was rolled in four passes with fixation of the values of thickness and rolling force. The results are summarized in four lines corresponding to each pass (Table 1). Based on the results of Table 1, the graphs of the dependence of the rolling force on the temperature of the IDS were plotted (Figs. 1, 2, 3 and 4). The numbers next to the red marks indicate the thickness of the sample after each rolling pass.

Table 1.The results of cold rolling of samples with thickness 1.86 mm in four passes

№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN	№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN
Sample 1, 1.83 mm, 25°C	1	1.59	10.1	Sample 15, 1.84 mm, 425°C	1	1.58	10.6
	2	1.2	13.7		2	1.26	25.8
	3	0.91	41.5		3	0.91	48
	4	0.58	101.8		4	0.59	91.8
Sample 2, 1.84 mm, 50°C	1	1.6	11.2	Sample 16, 1.84 mm, 450°C	1	1.57	6
	2	1.27	15.2		2	1.26	29.3
	3	0.93	52.4		3	0.9	55.4
	4	0.59	101.2		4	0.57	92.6
Sample 3, 1.83 mm, 100°C	1	1.6	15.5	Sample 17, 1.84 mm, 475°C	1	1.57	11.1
	2	1.27	19.2		2	1.26	23.7
	3	0.92	43.9		3	0.9	49.3
	4	0.58	99.6		4	0.58	90.5
Sample 4, 1.85 mm,	1	1.6	18.3	Sample 18, 1.85 mm,	1	1.58	15.2
	2	1.27	11.8		2	1.26	29.8

№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN	№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN
150°C	3	0.92	48.4	500°C	3	0.9	54.6
	4	0.57	95.3		4	0.56	91.5
Sample 5, 1.83 mm, 175°C	1	1.6	19.5	Sample 19, 1.84 mm, 525°C	1	1.57	15.2
	2	1.28	17.2		2	1.26	27.3
	3	0.93	51.6		3	0.9	56.6
	4	0.59	103.8		4	0.57	93
Sample 6, 1.84 mm, 200°C	1	1.59	13.4	Sample 20, 1.84 mm, 550°C	1	1.58	11.5
	2	1.27	17.5		2	1.25	25.2
	3	0.92	48.8		3	0.89	49.4
	4	0.52	102.3		4	0.55	87.2
Sample 7, 1.85 mm 225°C	1	1.6	8.2	Sample 21, 1.84 mm, 575°C	1	1.58	6.3
	2	1.28	21.3		2	1.25	21.1
	3	0.92	48.4		3	0.9	55
	4	0.59	103.2		4	0.57	85.6
Sample 8, 1.83 mm, 250°C	1	1.59	17.3	Sample 22, 1.84 mm, 600°C	1	1.57	10.8
	2	1.27	19.1		2	1.25	20.7
	3	0.91	50.5		3	0.9	58
	4	0.59	102.8		4	0.57	93.3
Sample 9, 1.85 mm, 275°C	1	1.59	11.3	Sample 23, 1.83 mm, 625°C	1	1.6	15.5
	2	1.26	24.2		2	1.27	27.1
	3	0.92	55.5		3	0.9	59
	4	0.58	96.9		4	0.57	91.7
Sample 10, 1.83 mm, 300°C	1	1.58	7.3	Sample 24, 1.84 mm, 650°C	1	1.58	16.3
	2	1.27	27.3		2	1.25	23.9
	3	0.92	57		3	0.91	60.3
	4	0.58	94.6		4	0.57	89.3
Sample 11, 1.84 mm, 325°C	1	1.59	9.1	Sample 25, 1.85 mm, 675°C	1	1.6	17.2
	2	1.27	24.4		2	1.26	34.7
	3	0.91	54.8		3	0.91	60.8
	4	0.58	100.9		4	0.58	94.6
Sample 12, 1.83 mm, 350°C	1	1.59	12.7	Sample 26, 1.83 mm, 700°C	1	1.62	19.9
	2	1.26	19.3		2	1.28	34.1
	3	0.9	53.1		3	0.92	64.4
	4	0.58	86.6		4	0.57	92
Sample 13, 1.83 mm, 375°C	1	1.57	14	Sample 27, 1.85 mm, 725°C	1	1.57	12.2
	2	1.25	17.7		2	1.25	27.1
	3	0.9	52.3		3	0.9	58.2
	4	0.57	85.6		4	0.57	88.6
Sample 14, 1.83 mm, 400°C	1	1.57	18	Sample 28, 1.83 mm, 750°C	1	1.57	13
	2	1.25	22		2	1.24	23.5
	3	0.9	43.3		3	0.89	53.6
	4	0.56	85.3		4	0.57	89.1

According to temperature analysis, graphic support is mandatory. Tabular representation is necessary for technological correction of cold rolling passes. Therefore, here are two options. This is the advantage of physicochemical analysis. In this case, according to four figures with an enlarged scale on the vertical, an important fact is revealed.

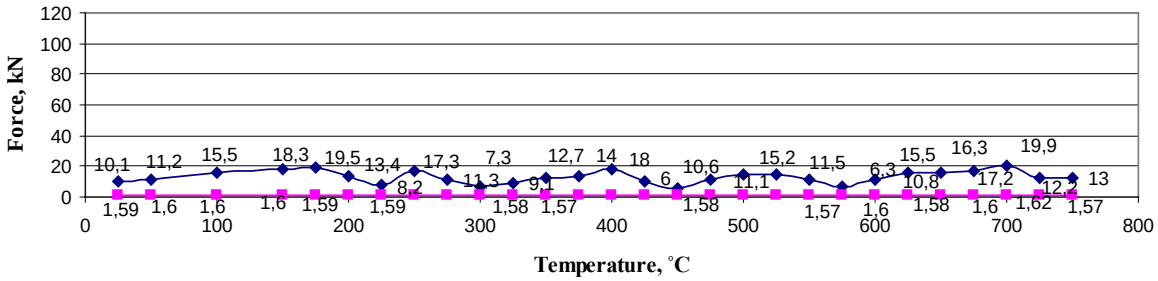

Fig. 1. The dependence of the rolling force on the temperature of the IDS (1) samples at the first pass

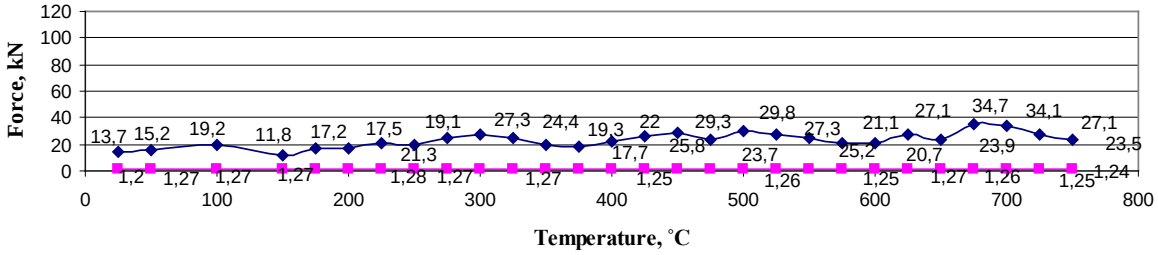

Fig. 2. The dependence of the rolling force on the temperature of the IDS (2) samples at the second pass

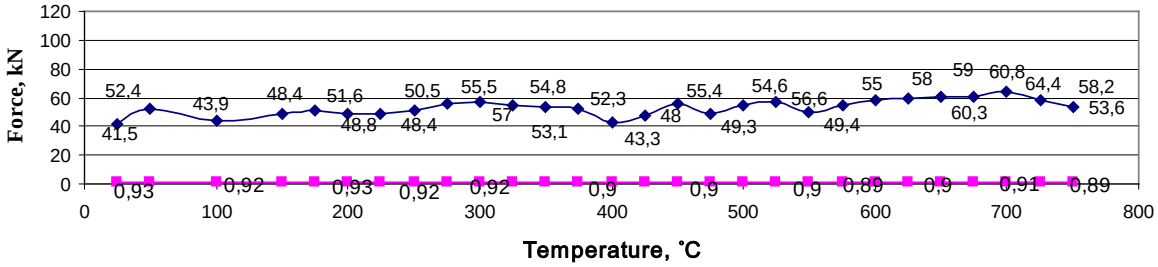

Fig. 3. The dependence of the rolling force on the temperature of the IDS (3) samples at the third pass

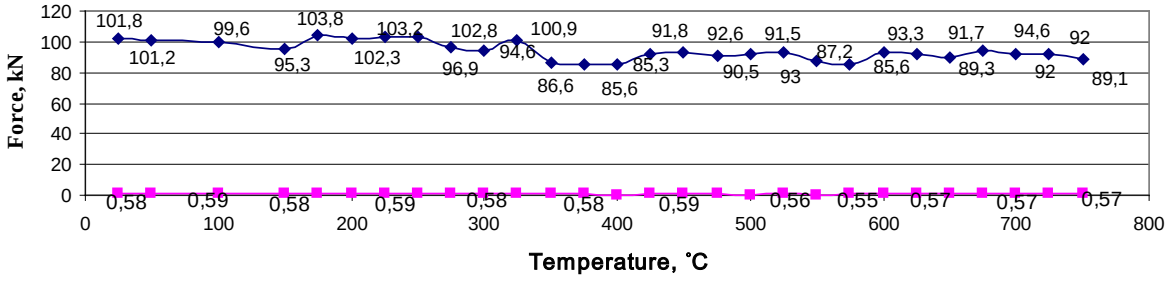

Fig. 4. The dependence of the rolling force on the temperature of the IDS (4) samples at the fourth pass

At the first pass, the heating by the IDS method could not be done, heating, even at high temperatures, does not promote the rolling. And further increase in the load on the second and third pass, on the contrary, requires an increase in effort [22 – 24]. Only in the fourth pass, when the average force has doubled, the temperature effect gives an effect. In all cases, the lines have active kinks. These places of probable discontinuities near stationary temperatures are called "orthogonal" areas and they are strictly tied to the temperature axis. The imposition of discrete series gives the following. For 171.5°C, there is an "orthogonal" section of the transition through the value of Tp, as required by TmA, and for 514.5 °C it is "orthogonal" for loads at the fourth pass. For the second series, the "orthogonality" of 343°C and 686°C is also observed for the second pass, but there is a maximum at 686°C. This indicates the stability of the fragments of the structure, so this mode is not recommended. Increased effort on the aisles has not yet been substantiated [25].

The second investigated cold-rolled Al-Li-Mg sheet with thickness 5.3 mm. Samples of 30 mm wide and 50 mm long were also cut out of it in an amount of 18 pieces. Before rolling, this group was divided into two parts: 10 pieces and 8 pieces. In each lot, the individual mode of IDS was tested with its temperature and holding time in a thermograph for two or three minutes (Tables 2, 3). According to the results of Tables 2 and 3, the graphs of the dependence of the rolling force on the temperature of the IDS were plotted (Fig. 5,6 and 7,8).

Table 2. Results of cold rolling of the first batch of samples with a thickness 5.3 mm for two passes

№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN	№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN
№ 1 IDS 330°C 3.0 min, 4.83 mm	1	2.84	121	№ 2 IDS 350°C 3.0 min, 4.86 mm	1	2.95	96.5
	2	1.41	236.3		2	1.54	185.8
№ 3 IDS 520°C 3.0 min, 4.85 mm	1	2.82	78.7	№ 4 IDS 670°C 3.0 min, 4.85 mm	1	2.84	83.9
	2	1.52	193		2	1.5	184.7
№ 5 IDS 695°C 3.0 min, 5.2 mm	1	3.43	-	№ 6 IDS 750°C 3.0 min, 4.80 mm	1	3.15	72.1
	2	1.9	-		2	1.72	107.8
№ 7 IDS 800°C 3.0 min, 5.2 mm	1	3.2	85.3	№ 8 IDS 840°C 3.0 min, 4.81mm	1	3.65	85.3
	2	1.67	103		2	-	-
№ 9 IDS 865°C 3.0 min, 4.93 mm	1	3.75	103.9	№ 10 IDS 900°C 3.0 min, 4.85 mm	1	4.1	65.1
	2	2.17	75.1		2	-	-

Samples of thickness 5.3 mm at high forces show the work of the second series (1) 343°C, 646°C and 514.5°C separates the intervals and shows that the volume of the sample is stably differentiated into plastic regions with respect to temperature. The use of such exaggerated efforts justifies the confidence of the TmA theory, but technologically for large thicknesses of the sample the effort should be lower, and the number of passes will increase [26]. At the first pass there are higher temperatures, so that the second interval will represent a fully 857.5°C rise shows the phase discontinuity related to the joint of the two regions forming different volumes in terms of stability.

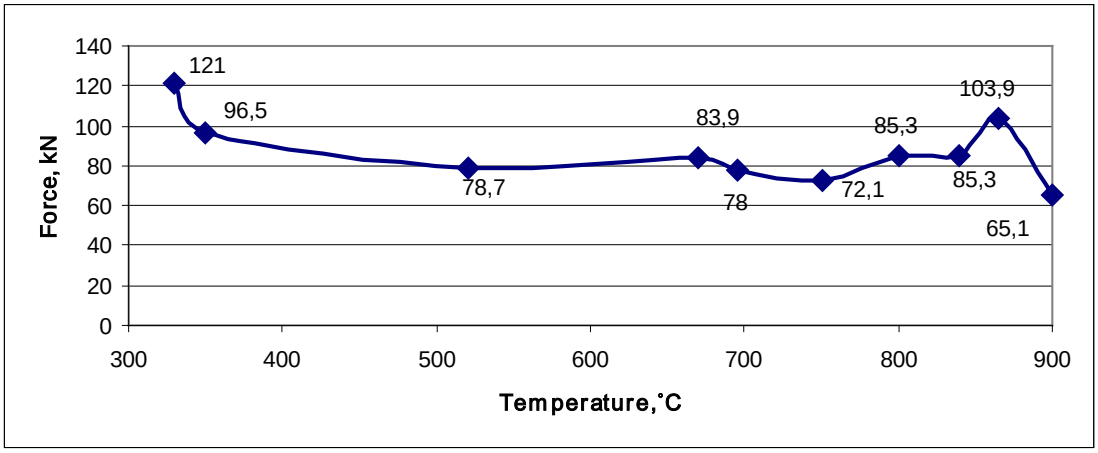

Fig. 5. The dependence of the rolling force on the temperature of the IDS (1) of the samples of the first batch with thickness of 5.3 mm at the first pass

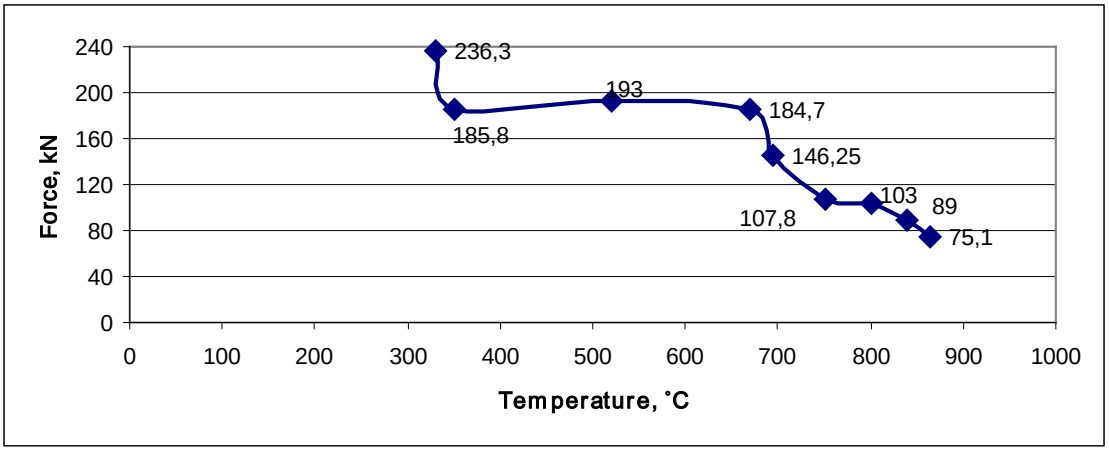

Fig. 6. The dependence of the rolling force on the temperature of the IDS (1) of the samples of the first batch with thickness of 5.3 mm at the second pass

The rolling of the second batch shows that in the intervals between the selected loads there are transformations of the transition structures. Obviously, the formation of the dominant region can be established, the maximum at 646°C, and with increasing force, the maximum is more pronounced while in the first batch it has a clearly "orthogonal" form [27].

The nature of the change in the rolling forces, taking into account the influence of the thickness of the Al-Li-Mg sheet sample, shows that the necessary individual choice of cobbing of the samples along the rolling passes is in good agreement with the series (1) of stationary temperatures of the thermal and force nature of the processes. This was clearly seen before the connection with discrete series was established in [7, 28 – 30]. In the next paper, it was assumed that when rolling samples at different thicknesses, registering thermal effects,

one can determine those modes of passages that were not previously available and had limitations on the fragmentation limit. To complete the real picture of the structural changes in Al-Mg-Li material, data on the texture are needed that will link the conditions for regulating the anisotropy of properties and the amorphization regimes in the border regions of the structural elements of the sample. In other words, the thermal effect can be accurately rationed as a disturbing factor, which causes the development of local structure dynamics. This serves as the basis for applying the methods of physics of granular materials – stereoisomeric parametrization of the structure, which are universal in the sense of addressing structures at different scales [9, 31].

Table 3. Results of cold rolling of the second batch of samples with a thickness of 5.3 mm in two passes

№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN	№ Sample, original thickness. IDS temperature, °C	Pass cold rolling	Thickness, mm	Force, kN
№ 1 IDS 800°C 1.5 min, 4.85 mm	1	3.13	87.6	№ 2 IDS 740°C 2.0 min, 4.87 mm	1	3.17	91.9
	2	1.66	124.7		2	1.65	132
№ 3 IDS 710°C 2.0 min, 4.82 mm	1	3.15	91.5	№ 4 IDS 680°C 2.0 min, 4.84 mm	1	3.14	89.6
	2	1.67	124.1		2	1.65	126.2
№ 5 IDS 650°C 2.0 min, 4.85 mm	1	3.17	98.3	№ 6 IDS 590°C 2.0 min, 4.84 mm	1	3.15	93.8
	2	1.7	147		2	1.67	124.9
№ 7 IDS 620°C 2.0 min, 4.85 mm	1	3.14	88.2	№ 8 IDS560°C 2.0 min, 4.85 mm	1	3.17	96.5
	2	1.65	120.7		2	1.66	124.5

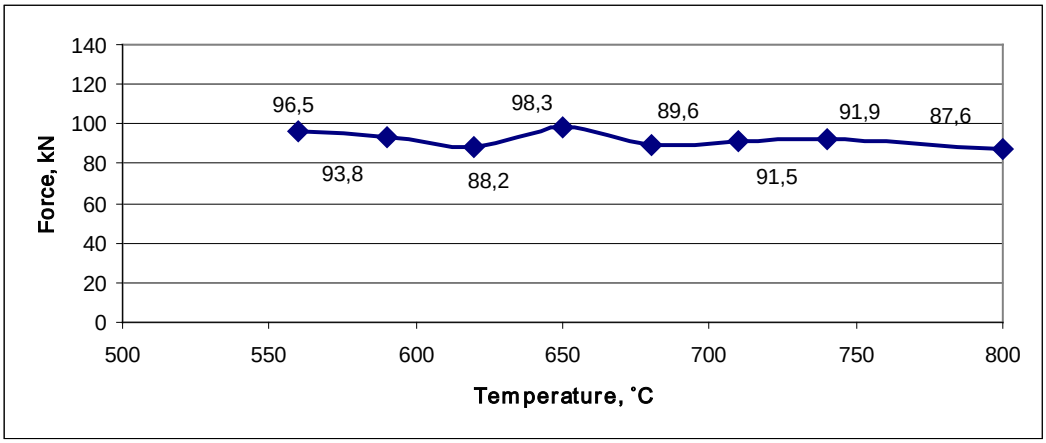

Fig. 7. The dependence of the rolling force on the temperature of the IDS (1) of the samples of the second batch with thickness of 5.3 mm at the first pass

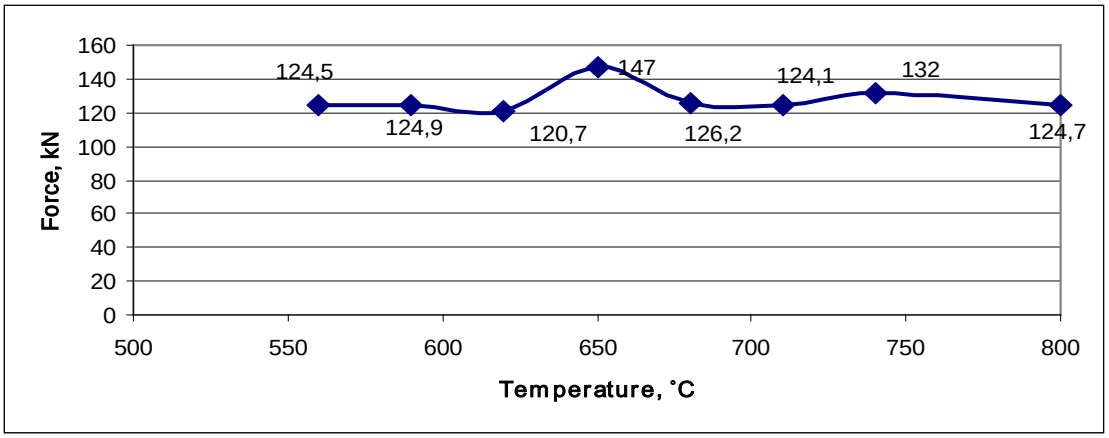

Fig. 8. The dependence of the rolling force on the temperature of the IDS (2) of the samples of the second batch with thickness of 5.3 mm at the second pass

4. Conclusions

Taking into account the influence on the rolling force of the initial thickness of the Al-Mg-Li sheet sample gives reliable guidelines for the search for the optimal rolling mode for sheet materials. It is also possible to use this approach for other initial thicknesses by means of a certain recalculation in terms of the change in the symmetry of the order parameter and the selection of the IDS modes, depending on the displacement to the stationary temperatures and temperatures of the power series.

The results obtained serve to select the mode of preliminary thermal activation by the IDS method. This greatly simplifies the processing of results in connection with the connection to the intervals of stationary temperatures and improves the accuracy of the impact evaluation.

The presence of a periodic dependence of the rolling force of the samples on their temperature, the IDS, can be used to quantify the parametrization of the participation of local quasi-liquid structures that affect the plasticity of the deformed material, as was previously established for granular materials.

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