PRESSURE TREATMENT OF METALS / ОБРАБОТКА МЕТАЛЛОВ ДАВЛЕНИЕМ

UDC 621.77
https://doi.org/10.17073/0021-3438-2024-4-43-53

Research article
Научная статья

Capabilities of asymmetric rolling of single-layer and laminated materials made from aluminum and its alloys

O.D. Biryukova[1], **A.E. Mogilnykh**[1], **A.M. Pesin**[1], **D.O. Pustovoytov**[1],
I.A. Pesin[1], **M.A. Biryukov**[2]

[1] **Nosov Magnitogorsk State Technical University**
38 Lenin Prosp., Magnitogorsk, Chelyabinsk Region 455000, Russia

[2] **PJSC "Magnitogorsk Iron and Steel Works"**
93 Kirov Str., Magnitogorsk, Chelyabinsk Region 455000, Russia

✉ Olesya D. Biryukova (fimapatisonchik@inbox.ru)

Abstract: Asymmetric rolling of aluminum alloys is one of the methods for improving their mechanical and performance characteristics. Kinematic asymmetry during rolling is achieved by varying the roll speed ratios (V_1/V_2). It is believed that when $V_1/V_2 > 3$, the process of asymmetric rolling, by combining significant compression and shear deformations, approximates the processes of severe plastic deformation. It has been found that the majority of studies are based on data obtained within a limited roll speed ratio range, $V_1/V_2 < 2$, in asymmetric rolling. This article examines the effects observed at $V_1/V_2 = 1 \div 7.7$. The implementation of this condition became possible thanks to a unique scientific facility – the 400 laboratory-industrial asymmetric rolling mill at the Zhilyaev laboratory "Mechanics of Gradient Nanomaterials" at Nosov Magnitogorsk State Technical University Experiments were conducted on asymmetric thin-sheet rolling of aluminum alloys 2024, 5083, and 6061, as well as accumulative roll bonding to produce laminated sheet aluminum composites 5083/2024, 5083/1070, and 6061/5083. The disadvantages of asymmetric rolling compared to symmetric rolling were identified: sample failure was observed at single relative reductions of 37 % for layered sheet aluminum composites (5083/2024) and 40 % for thin-sheet aluminum alloys (6061). The nuances of material preparation for processing were described, including the necessity of cleaning and degreasing the alloy surfaces before bonding into a composite. The rolling temperature regimes were selected, determining cold asymmetric thin-sheet rolling (room temperature processing) and warm asymmetric accumulative roll bonding (heating of the workpieces in the furnace before rolling at 320–350 °C). A reduction in rolling force (by a minimum of 1.3 times), the ability to vary hardness (including an increase by a minimum of 30 %), and technological plasticity with changes in the roll speed ratios within the range of 2 to 7.7 were demonstrated. Options were proposed for reducing the processing cycles of aluminum alloys without compromising the quality of the finished product by reducing the number of rolling passes and annealing steps in the standard process scheme.

Key words: asymmetric rolling, accumulative roll bonding, severe plastic deformation, technological plasticity, hardness, kinematic asymmetry, rolling force.

Acknowledgements: This research was supported by the Russian Science Foundation grant (agreement No. 23-79-30015).

For citation: Biryukova O.D., Mogilnykh A.E., Pesin A.M., Pustovoytov D.O., Pesin I.A., Biryukov M.A. Capabilities of asymmetric rolling of single-layer and laminated materials made from aluminum and its alloys. *Izvestiya. Non-Ferrous Metallurgy.* 2024;30(4):43–53.
https://doi.org/10.17073/0021-3438-2024-4-43-53

Возможности асимметричной прокатки однослойных и слоистых материалов из алюминия и его сплавов

О.Д. Бирюкова[1], А.Е. Могильных[1], А.М. Песин[1], Д.О. Пустовойтов[1], И.А. Песин[1], М.А. Бирюков[2]

[1] **Магнитогорский государственный технический университет им. Г.И. Носова**
Россия, 455000, Челябинская обл., г. Магнитогорск, пр. Ленина, 38

[2] **ПАО «Магнитогорский металлургический комбинат»**
Россия, 455000, Челябинская обл., г. Магнитогорск, ул. Кирова, 93

✉ Олеся Дмитриевна Бирюкова (fimapatisonchik@inbox.ru)

Аннотация: Асимметричная прокатка алюминиевых сплавов является одним из способов улучшения их механических и эксплуатационных характеристик. Кинематическая асимметрия при прокатке осуществляется при варьировании отношений скоростей рабочих валков (V_1/V_2). Считается, что при $V_1/V_2 > 3$ процесс асимметричной прокатки по механизму совмещения больших деформаций сжатия и сдвига приближен к процессам интенсивной пластической деформации. Выявлено, что большее количество исследований основано на данных, полученных при ограниченном диапазоне соотношения скоростей валков $V_1/V_2 < 2$ при асимметричной прокатке. В статье рассмотрены эффекты, полученные при $V_1/V_2 = 1 \div 7{,}7$. Реализация данного условия стала возможна благодаря уникальной научной установке – лабораторно-промышленному стану 400 асимметричной прокатки лаборатории «Механика градиентных наноматериалов им. А.П. Жиляева» МГТУ им. Г.И. Носова. Проведены эксперименты по асимметричной тонколистовой прокатке алюминиевых сплавов 2024, 5083 и 6061 и аккумулирующей прокатке с получением листовых слоистых алюминиевых композитов 5083/2024, 5083/1070 и 6061/5083. Выявлены недостатки асимметричной прокатки по сравнению с симметричной: наблюдалось разрушение образцов при единичных относительных обжатиях от 37 % для листовых слоистых алюминиевых композитов (5083/2024) и от 40 % – для тонколистовых алюминиевых сплавов (6061). Описаны нюансы подготовки материала к обработке, в том числе необходимость зачистки и обезжиривания поверхности сплавов перед соединением в композит. Подобраны температурные режимы прокатки, определившие холодную асимметричную тонколистовую прокатку (комнатная температура обработки) и теплую асимметричную аккумулирующую прокатку (температура нагрева заготовок в печи перед прокаткой 320–350 °С). Показаны снижение силы прокатки (минимально в 1,3 раза), возможность варьирования твердости (в том числе увеличения минимально на 30 %) и технологической пластичности при изменении отношений скоростей валков в пределах от 2 до 7,7. Предложены варианты сокращения технологических циклов обработки алюминиевых сплавов без снижения качества готовой продукции путем уменьшения количества прокаток и отжигов в стандартной схеме.

Ключевые слова: асимметричная прокатка, аккумулирующая прокатка, интенсивная пластическая деформация, технологическая пластичность, твердость, кинематическая асимметрия, сила прокатки.

Благодарности: Исследования выполнены за счет гранта РНФ (соглашение № 23-79-30015).

Для цитирования: Бирюкова О.Д., Могильных А.Е., Песин А.М., Пустовойтов Д.О., Песин И.А., Бирюков М.А. Возможности асимметричной прокатки однослойных и слоистых материалов из алюминия и его сплавов. *Известия вузов. Цветная металлургия.* 2024;30(4):43–53. https://doi.org/10.17073/0021-3438-2024-4-43-53

Introduction

In line with the Metallurgical Industry Development Strategy of the Russian Federation through 2030[1], a series of objectives has been set, focusing on the production of high-quality metal products. Notably, under these conditions, the non-ferrous metallurgy sector is expected to achieve production growth, not only to meet import substitution goals but also to support the export of high-quality, competitive products. The development of new ultra-strong yet lightweight materials is crucial for driving technological progress in industries such as aerospace, electrical engineering, automotive, and aviation manufacturing. Aluminum and its alloys

---

[1] Order of the Government of the Russian Federation of December 28, 2022 No. 4260-r “On approval of the strategy for the development of the metallurgical industry of the Russian Federation for the period up to 2030”.

are the primary materials of choice for structural design in these fields.

Achieving high-quality aluminum rolled products depends on processing methods that aim to comprehensively improve the materials' properties, structure, and geometric parameters. For instance, asymmetric rolling is a promising technique for producing high-quality materials, as it improves mechanical properties such as strength, hardness, and plasticity, along with performance characteristics like formability under pressure and technological plasticity [1—10]. Asymmetry during rolling can be achieved in several ways: varying the roll speed ratio to induce kinematic asymmetry; changing the roll diameter ratio to create geometric asymmetry; or modifying the surface of the working rolls or the material itself to introduce physical-mechanical or contact asymmetry [11—14]. Among these, kinematic asymmetry is the most technologically viable and often preferred. Currently, asymmetric rolling with a roll speed ratio of $V_1/V_2 > 3$ is regarded as a metal forming process that closely approximates the effects of severe plastic deformation. Its key feature lies in the ability to combine significant compression and shear deformations by employing a simple and pure shear scheme, which impacts the deformability of metals and alloys.

It has been established that asymmetric rolling significantly increases the hardness and strength of materials [15—19], though plasticity tends to decrease, necessitating intermediate and final heat treatments of the rolled metal. However, combining high levels of reduction with specific roll speed ratios can maintain or even It's important to note that in most foreign publications [20—23], researchers typically explore a narrow range of roll speed ratios, with V_1/V_2 not exceeding 2. There is a noticeable lack of data on the effects of a broader roll speed ratio range ($V_1/V_2 = 2 \div 10$) in both Russian and international studies, making this an area of significant interest.

The implementation of asymmetric rolling with kinematic asymmetry and roll speed ratios ranging from 1.05 to 10.0 has been made possible thanks to a unique scientific facility (USF)[1] — the 400 laboratory-industrial asymmetric rolling mill[2] at the Zhilyaev laboratory "Mechanics of Gradient Nanomaterials" at Nosov Magnitogorsk State Technical University. This equipment has no equivalent in Russia, with the most similar system located in South Korea, where the roll speed ratio can reach up to 2.

Research methodology

The study investigated the effect of kinematic asymmetry during thin-sheet and accumulative rolling on the changes in mechanical properties of aluminum alloys. The asymmetric rolling was carried out on the USF "Asymmetric Rolling Mill 400" at room temperature. No lubricants were used; however, pre-rolling of aluminum was performed to promote its adhesion to the roll surfaces, thereby increasing friction coefficient. The aluminum alloys subjected to rolling were from the 1xxx, 2xxx, 5xxx, and 6xxx series, specifically 1070, 2024, 5083, and 6061, whose chemical compositions are presented in Table 1. The selection of these alloys was based on their widespread use and popularity in the manufacturing industries for which this research was conducted (automotive, aerospace, etc.).

Aluminum alloys 2024, 5083, and 6061 were processed using asymmetric rolling with relative reductions ranging from 5 to 89 % and roll speed ratios V_1/V_2 from 1 to 7.7. The workpiece dimensions were as follows, in mm: thickness — from 1.9 to 6, width — 25, length — 100. No additional heat treatment or preheating was applied prior to rolling.

Certain parameters of asymmetric thin-sheet and asymmetric accumulative roll bonding differed, which was determined by the technological features of the process: thin-sheet rolling involved processing single-layer aluminum alloys, while accumulative roll bonding, the general scheme of which is shown in Fig. 1 [24], was intended for laminated materials forming a composite.

These methods are used to obtain an ultrafine-grained structure, with the accumulative roll bonding process involving not only the combined and simple shear schemes but also the accumulation of stresses after each processing cycle. However, the complexity of this process, compared to asymmetric thin-sheet rolling, lies in the necessity of preparing the alloy surfaces for bonding during processing. Some studies [24—27] describe the requirement for preliminary mechanical joining of the sheets, which improves the adhesion level during rolling. This was performed on several workpieces, as shown in Fig. 2.

During asymmetric accumulative roll bonding, aluminum alloys 1070, 2024, 5083, and 6061 were used to create laminated sheet aluminum composites 5083/1070, 5083/2024, and 6061/5083. For these materials, two rolling cycles were conducted in all cases, with relative reductions ranging from 45 to 75 % (except in cases where samples were destroyed after the first

---

[1] https://ckp-rf.ru/catalog/usu/3206908

[2] http://lmgn.magtu.ru/ru/oborudovanie.html

Table 1. **Chemical composition (%) of aluminum alloys from various series**

Таблица 1. Химический состав (%) алюминиевых сплавов различных серий

Alloy	Mn	Mg	Si	Fe	Cu	Cr	Ti	Zn	Al
1070	0.03	0.02	0.15	0.16	0.01	–	0.01	0.04	99.70
2024	0.019	0.473	0.422	0.178	0.02	0.001	0.15	0.25	98.487
5083	0.682	4.479	0.091	0.285	0.027	0.104	0.007	0.014	94.282
6061	0.90	1.00	0.60	0.70	0.32	0.22	0.15	0.25	95.86

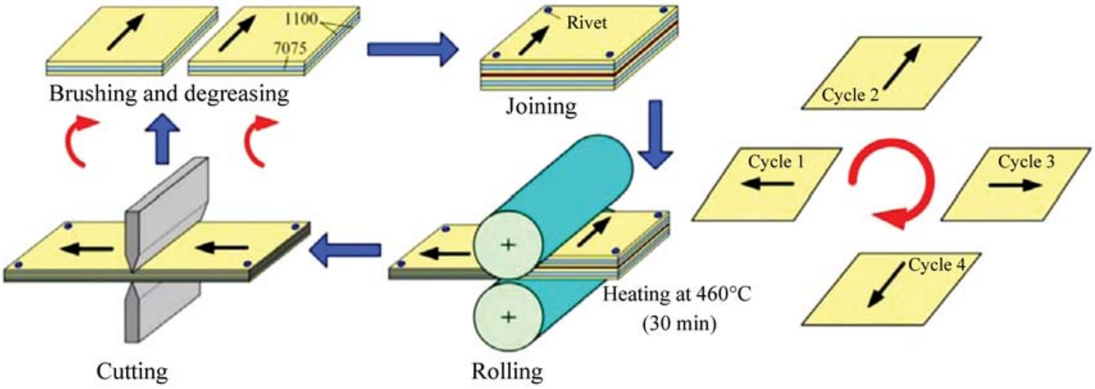

Fig. 1. Scheme of accumulative roll bonding [24]

Рис. 1. Схема аккумулирующей прокатки [24]

Fig. 2. Workpieces prepared for asymmetric accumulative roll bonding with preliminary joining using thin wire

Рис. 2. Образцы, подготовленные для асимметричной аккумулирующей прокатки с предварительным соединением их тонкой проволокой

rolling cycle). The roll speed ratio V_1/V_2 ranged from 1 to 5. The workpieces had the following dimensions, in mm: the thickness of individual layers composing the composite ranged from 1 to 2, with the total thickness of the two alloys being between 2 and 4; the width was 50, and the length was 100. The rolling temperature conditions varied from cold to hot, with preheating of the workpieces to 320—350 °C typically applied. The surface of each alloy (only for the cold asymmetric accumulative roll bonding method) was pre-treated by cleaning with wire brushes or sandpaper, followed by degreasing with a solvent. Subsequent transport to the rolling mill was carried out immediately to prevent the formation of a new thick oxide layer.

Results and discussion

In symmetric cases (при $V_1/V_2 = 1$), all workpieces failed during the first pass, both in thin-sheet rolling and cold accumulative roll bonding, when the single relative reduction was 40 % or higher. The results are shown in Table 2 and Fig. 3.

The study also revealed that improper or insufficiently thorough pre-cleaning and subsequent degreasing of the surface before accumulative roll bonding (at any roll speed ratio) negatively affected the formation of the transition layer, which is created through diffusion interactions. This resulted in a low degree of layer interpenetration between the base metals and alloys, leading to microcracks at the layer interfaces and areas with partial lack of bonding between the layers.

The necessity of pre-joining the alloys to form a laminated material, as shown in Fig. 2, was not confirmed — at low reductions, this "bond" had no positive effect, as the layers would separate, and the wire would break. For reductions exceeding 50 %, such pre-joining was unnecessary, as the layers bonded equally well regardless of the presence or absence of wire. In some cases, the wire had a negative effect, leading to defects at the front and rear ends of the rolled material.

It was also found that the formation of laminated sheet composites in the cold processing mode is only possible when joining identical alloys in the first cycle (e.g., alloy 5083 + alloy 5083 or alloy 1070 + alloy 1070). The first and second cycles with dissimilar alloys (e.g., alloy 5083 + alloy 2024 or alloy 6061 + alloy 5083) must be conducted in the warm rolling mode with preheating to 320—350 °C (considering material cooling during transport from the furnace to the rolling mill). Hot deformation of laminated sheet aluminum composites was performed by heating the workpieces to 420—500 °C, which produced unsatisfactory results, as all workpieces developed defects such as "over-squeezing" and "waviness". Table 3 presents some parameters of the asymmetric accumulative roll bonding modes—preheating temperatures for different types of materials (homogeneous 6061/6061, 5083/5083, 1070/1070, and heterogeneous 5083/1070, 5083/2024, 6061/5083) prior

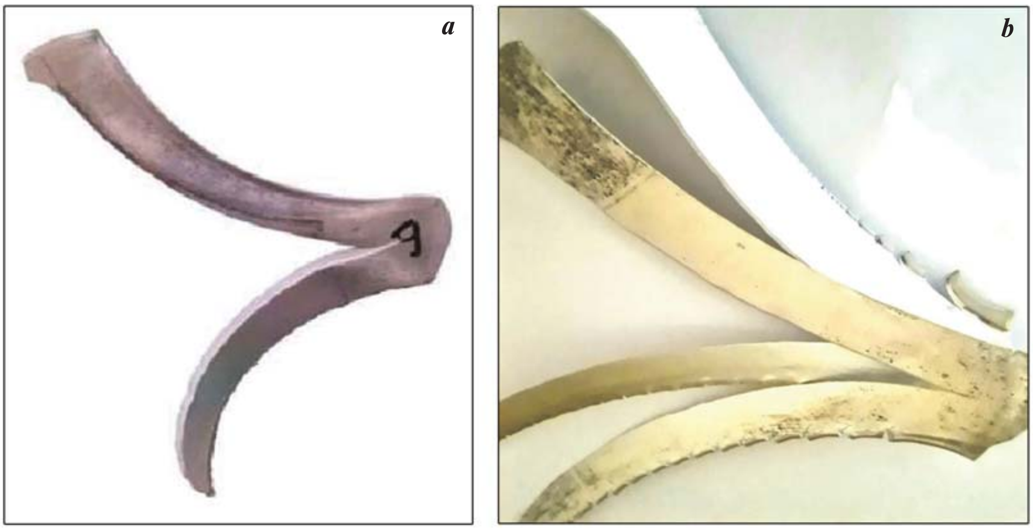

Fig. 3. Workpieces after symmetrical thin-sheet rolling (***a***) and accumulative (***b***) roll bonding

Рис. 3. Образцы после симметричной тонколистовой (***a***) и аккумулирующей (***b***) прокаток

Table 2. **Results of symmetrical thin-sheet rolling and accumulative roll bonding of aluminum alloys**

Таблица 2. Результаты симметричной тонколистовой и аккумулирующей прокаток алюминиевых сплавов

Material	Thickness, mm		Relative reduction, %	Force, kN
	Initial	Final		
2024	6.00	3.10	48	464
5083	1.90	0.95	50	290
6061	2.00	1.20	40	353
5083/2024	3.00	1.90	37	1330
5083/1070	3.00	1.60	47	900
6061/5083	3.00	1.55	48	1200

to rolling, the cycle number of asymmetric accumulative roll bonding, the relative reduction, and the integrity of the workpieces after processing, including the likelihood of defects that could affect further material processing.

The key advantages of asymmetric rolling compared to symmetric rolling have been identified: a reduction in rolling force, the ability to control mechanical properties (including hardness, strength, and plasticity) depending on the level of asymmetry, and an increase in technological plasticity. These advantages are characteristic of both thin-sheet rolling and accumulative roll bonding, as shown in Table 4 (using alloy 6061 processed in one pass and laminated sheet composite 6061/5083 processed in two cycles as examples). During asymmetric accumulative roll bonding, the preheating of the workpieces was carried out for 10—15 minutes at a temperature of 320 °C. All the presented workpieces maintained their integrity after processing.

It is important to note that asymmetric rolling significantly increases technological plasticity. This parameter is taken into account when developing new technical and technological solutions for material processing. Below are experimental data comparing symmetric and asymmetric rolling (using aluminum alloy 6061 as an example), clearly demonstrating the difference in the deformability of the workpieces. The ultimate goal of the experiment was to obtain a strip with a thickness of 0.5 mm. In the case of symmetric rolling, this result was achieved in 4 passes. After each pass, heat treatment, specifically annealing, was required, meaning it was performed 4 times. The roll gap was set to a relative reduction of 35 % for the first three passes and 9 % for the final pass. Any reduction greater than 35 % led to the workpiece's integrity being compromised, i.e., resulting in its failure. The results are presented in Table 5.

During asymmetric rolling, the roll speed ratio was $V_1/V_2 = 2$ (in passes 1 and 2), allowing the rolling process to be carried out with a relative reduction of 63 % without damaging the workpieces. As shown by the data in Table 6, the target was achieved in just two passes. The number of annealing treatments was also reduced to two.

With a further increase in kinematic asymmetry to $V_1/V_2 = 4$, the relative reduction without material

Table 3**. Parameters of the asymmetric accumulative roll bonding modes for aluminum alloys (comparison of temperature conditions)**

Таблица 3. Параметры режимов асимметричной аккумулирующей прокатки алюминиевых сплавов (сравнение температурных условий)

Material	Preheating temperature of the aluminum composite, °C	Cycle No.	Relative reduction, %	Defects Preservation of workpiece integrity
6061/6061 5083/5083 1070/1070	–	1	50	+
5083/1070 5083/2024 6061/5083	–	1	50	Delamination (integrity not preserved)
5083/1070 5083/2024 6061/5083	320–350	1	50	+
5083/1070 5083/2024 6061/5083	320–350	2	50	+
5083/1070 5083/2024 6061/5083	420–500	1	50	Waviness and over-squeezing (integrity preserved, but cycle 2 is not possible)

failure reached 75 %. It is clear that with asymmetric rolling at a roll speed ratio of $V_1/V_2 = 4$, only one pass and one final annealing were required (see Table 6).

Similar results were observed during accumulative roll bonding. It was shown that in cold symmetric accumulative roll bonding, the workpieces failed at a relative reduction of 42 %. Additionally, this level of relative reduction was insufficient for bonding the workpieces in the deformation zone, which resulted in either incomplete bonding of the metal layers or tears in the middle of the samples, along with the "crescent-shaped" defect. Cold asymmetric rolling was characterized by a reduction in defect formation. All workpieces demonstrated good pressure weldabil-

Table 4. **Results of asymmetrical thin-sheet rolling and accumulative roll bonding of aluminum alloys (comparison of rolling force and hardness)**

Таблица 4. Результаты асимметричной тонколистовой и аккумулирующей прокаток алюминиевых сплавов (сравнение силы прокатки и твердости)

Material	Roll speed ratio	Relative reduction, %	Force, kN	Hardness, HB
6061	2	63	320	118
6061	3	70	228	121
6061	4	75	166	100
6061/5083	2	53	640	65/78
6061/5083	3	62	558	73/89
6061/5083	4	67	490	93/100

Table 5. **Experimental data on symmetrical rolling of aluminum strip made from alloy 6061**

Таблица 5. Экспериментальные данные симметричной прокатки алюминиевой ленты из сплава 6061

Pass No.	Thickness, mm		Relative reduction, %	Force, kN
	Initial	Final		
1	2.00	1.30	35	337
2	1.30	0.85	35	272
3	0.85	0.55	35	275
4	0.55	0.50	9	151

Table 6. **Experimental data on asymmetric rolling of aluminum strip made from alloy 6061**

Таблица 6. Экспериментальные данные асимметричной прокатки алюминиевой ленты из сплава 6061

Pass No.	Thickness, mm		Relative reduction, %	Force, kN
	Initial	Final		
$V_1/V_2 = 2$				
1	2.00	0.74	63	320
2	0.74	0.50	32	234
$V_1/V_2 = 4$				
1	2.00	0.50	75	166

ity. Technological plasticity increased significantly, making it possible to roll laminated aluminum composites with single relative reductions ranging from 75 to 95 %.

In warm asymmetric accumulative roll bonding, the maximum single relative reduction reached 98 %. At lower reductions (up to 75 %), an increase in the drawing ratio (calculated using the formula $\mu = l1/l0$ was observed with an increase in kinematic asymmetry to $V_1/V_2 = 4$ (the preheating temperature of the workpieces was 320 °C, and the initial total thickness of the alloys in the composite was 3 mm). The values of the drawing ratio for the laminated aluminum composite 5083/2024 at various roll speed ratios are presented below:

V_1/V_2	1.0	2.0	2.5	3.0	3.5	4.0
μ	1.60	3.00	3.58	3.92	4.40	5.06

Conclusion

In both Russia and abroad, a limited range of roll speed ratios is considered in asymmetric rolling. Thanks to modern equipment, specifically the USF — 400 laboratory-industrial asymmetric rolling mill at the Zhilyaev laboratory “Mechanics of Gradient Nanomaterials”, it has become possible to process metals and alloys at roll speed ratios $V_1/V_2 > 2$. Based on the results of experimental studies on asymmetric thin-sheet rolling and accumulative roll bonding, the following were demonstrated:

1. An increase in the technological plasticity of aluminum alloys (as exemplified by alloys 2024, 5083, and 6061) and laminated sheet aluminum composites (as exemplified by 5083/1070, 5083/2024, and 6061/5083). In thin-sheet rolling, it became possible to shorten the technological cycle of cold material processing, including reducing the number of rolling passes and annealing without compromising the quality of the rolled product. It was shown that instead of four standard passes in the symmetric mode, a single pass in the asymmetric mode is permissible. In accumulative roll bonding, a single relative reduction of 98 % can be achieved without material failure in the asymmetric mode, compared to 42 % in the symmetric mode. The drawing ratio increased from 1.60 to 5.06 as the roll speed ratio V_1/V_2 increased from 1 to 4 (as demonstrated with the laminated sheet aluminum composite 5083/2024).

2. The ability to control mechanical properties (as demonstrated with hardness) by adjusting the level of asymmetry at roll speed ratios V_1/V_2 in the range of 2 to 4.

3. A reduction in rolling force with an increase in the level of asymmetry: for example, for aluminum alloy 6061, the force decreased from 320 to 166 kN as the roll speed ratio V_1/V_2 increased from 2 to 4, and for the laminated sheet aluminum composite 6061/5083, the force decreased from 640 to 490 kN, respectively. Similar results were observed for other aluminum alloys and laminated sheet aluminum composites considered.

4. Specifics of preparing aluminum alloys for the production of laminated sheet aluminum composites, which include proper surface treatment before bonding and the lack of necessity for additional wire-based bonding of layers.

References

1. Youzhi Li, Yongfeng Shen, Sixin Zhao, Weina Zhang, Xue W.Y. Strengthening a medium-carbon low-alloy steel by nanosized grains: The role of asymmetrical rolling. *Nanomaterials*. 2023;13(5):956. https://doi.org/10.3390/nano13050956
2. Muñoz J.A., Avalos M., Schell N., Brokmeier H.G., Bolmaro R. Comparison of a low carbon steel processed by cold rolling (CR) and asymmetrical rolling (ASR): Heterogeneity in strain path, texture, microstructure and mechanical properties. *Journal of Manufacturing Processes*. 2021;64:557—575. https://doi.org/10.1016/j.jmapro.2021.02.017
3. Graça A., Vincze G., Wen W., Butuc M.C., Lopes A.B. Numerical study on asymmetrical rolled aluminum alloy sheets using the visco-plastic self-consistent (VPSC) method. *Metals*. 2022;12(6):979. https://doi.org/10.3390/met12060979
4. Tao Zhang, Lei Li, Shi-hong Lu, Jia-bin Zhang, Hai Gong. Comparisons of flow behavior characteristics and microstructure between asymmetrical shear rolling and symmetrical rolling by macro/micro coupling simulation. *Journal of Computational Science*. 2018;29:142—152. https://doi.org/10.1016/j.jocs.2018.10.005
5. Guofu Xu, Xiaowu Cao, Tao Zhang, Yulu Duan, Xiaoyan Peng, Ying Deng, Zhimin Yin. Achieving high strain rate superplasticity of an Al—Mg—Sc—Zr alloy by a new asymmetrical rolling technology. *Materials Science and Engineering: A*. 2016;672:98—107. https://doi.org/10.1016/j.msea.2016.06.070

6. Ji Wang, Xianghua Liu, Xiangkun Sun. Study on asymmetrical cold rolling considered sticking friction. *Journal of Materials Research and Technology*. 2020;9(6):14131—14141. https://doi.org/10.1016/j.jmrt.2020.10.027
7. Amegadzie M.Y., Bishop D.P. Effect of asymmetric rolling on the microstructure and mechanical properties of wrought 6061 aluminum. *Materials Today*. 2020;25:101283. https://doi.org/10.1016/j.mtcomm.2020.101283
8. Tao Zhang, Lei Li, Shi-Hong Lu, Hai Gong, Yun-Xin Wu. Comparisons of different models on dynamic recrystallization of plate during asymmetrical shear rolling. *Materials*. 2018;11(1):151. https://doi.org/10.3390/ma11010151
9. Cunqiang Ma, Longgang Hou, Jishan Zhang, Linzhong Zhuang. Influence of thickness reduction per pass on strain, microstructures and mechanical properties of 7050 Al alloy sheet processed by asymmetric rolling. *Materials Science and Engineering: A*. 2016;650(5): 454—468. https://doi.org/10.1016/j.msea.2015.10.059
10. Šlapáková M., Kihoulou B., Grydin O. Development of microstructure of asymmetrically rolled AA3003 aluminium sheets with Zr addition. *Journal of Alloys and Metallurgical Systems*. 2023;2:100012. https://doi.org/10.1016/j.jalmes.2023.100012
11. Muñoz J.A., Khelfa T., Duarte G.A., Avalos M., Bolmaro R., Cabrera J.M. Plastic behavior and microstructure heterogeneity of anAA6063-T6 aluminum alloy processed by symmetric and asymmetric rolling. *Metals*. 2022;12(10):1551. https://doi.org/10.3390/met12101551
12. Vincze G., Simões F., Butuc M.C. Asymmetrical rolling of aluminum alloys and steels: A review. *Metals*. 2020;10(9):1126. https://doi.org/10.3390/met10091126
13. Sułek B., Krawczyk J., Majewski M., Nawida N., Plewa K. Analysis of the influence of kinematic and frictionasymmetry on the curvature of the strip and forceparameters of the rolling process. *Tribologia*. 2023; 305(3):81—94. https://doi.org/10.5604/01.3001.0053.9439
14. Sai Wang, Xianlei Hu, Xiaogong Wang, Jingqi Chen, Xianghua Liu, Changsheng Li. Design and experiment of V-shaped variable thickness rolling for rolled profiled strips. *Journal of Materials Research and Technology*. 2021;15:4381—4396. https://doi.org/10.1016/j.jmrt.2021.10.067
15. Biryukova O.D., Pesin A.M., Pustovoytov D.O. Investigation of the influence of kinematic asymmetry on the properties of laminated materials. *Materials Research Proceedings*. 2023;32:287—293. https://doi.org/10.21741/9781644902615-33
16. Biryukova O., Pesin A., Pustovoitov D. Experience in obtaining laminated aluminum composites by asymmetric accumulative roll bonding. *Letters on Materials*. 2022;12(4):373—378. https://doi.org/10.22226/2410-3535-2022-4-373-378
17. Pustovoytov D., Pesin A., Tandon P. Asymmetric (hot, warm, cold, cryo) rolling of light alloys: A review. *Metals*. 2021;11(6):956. https://doi.org/10.3390/met11060956
18. Biryukova O., Pesin A., Pustovoytov D., Kozhemiakina A., Nosov L. Obtaining laminated aluminum composites with a gradient structure based on asymmetric deformation. *METAL*. 2021;496—501. https://doi.org/10.37904/metal.2021.4133
19. Pesin A., Raab G., Sverchkov A., Pustovoytov D., Kornilov G., Bochkarev A., Pesin I., Nosov L. Development of asymmetric cold rolling technology of high-strength steel grades in order to exclude intermediate annealing operations. *Materials Research Proceedings*. 2023;32: 355—361.
20. Kosturek R., Mróz S., Stefanik A., Szota P.L., Gębara P., Merda A., Wachowski M., Gloc M. Study on symmetry and asymmetry rolling of AA2519-T62 alloy at room-temperature and cryogenic conditions. *Materials*. 2022;15(21):7712. https://doi.org/10.3390/ma15217712
21. Pan D., Sansome D.H. An experimental study of the effect of roll-speed mismatch on the rolling load during the cold rolling of thin strip. *Journal of Mechanical Working Technology*. 1982;6(4):361—377. https://doi.org/10.1016/0378-3804(82)90034-1
22. Aboutorabi A., Assempour A., Afrasiab H. Analytical approach for calculating the sheet output curvature in asymmetrical rolling: In the case of roll axis displacement as a new asymmetry factor. *International Journal of Mechanical Sciences*. 2016;105:11—22. https://doi.org/10.1016/j.ijmecsci.2015.10.016
23. Qilin Zhao, Xianlei Hu, Xianghua Liu. Analysis of mechanical parameters in multi-pass asymmetrical rolling of strip by slab method. *Materials*. 2023;16(18):6286. https://doi.org/10.3390/ma16186286
24. Zejun Chen, Hongbo Hu, Xia Wu, Minhong Zhou, Kawunga Nyirenda, Qing Liu, Guojun Wang, Deman

Wang. Effect of cross accumulative roll bonding process on microstructure and mechanical properties of laminated 1100/7075 composite sheets. *TMS (The Minerals, Metals and Society)*. 2013;2285—2295. https://doi.org/10.1002/9781118792148.ch284

25. Mehtedi M.E., Lai D., Mohtadi R.E., Carta M., Buonadonna P., Aymerich F. Bonding of similar AA3105 aluminum alloy by accumulative roll bonding process. *ESAFORM*. 2021;942/1—942/11. https://doi.org/10.25518/esaform21.942
26. Seleznev M., Renzing C., Schmidtchen M., Prahl U., Biermann H., Weidner A. Deformation lenses in a bonding zone of high-alloyed steel laminates manufactured by cold roll bonding. *Metals*. 2022;12:590. https://doi.org/10.3390/met12040590
27. Karganroudi S.S., Nasab B.H., Rahmatabadi D., Ahmadi M., Gholami M.D., Kasaeian-Naeini M., Hashemi R., Aminzadeh A., Ibrahim H. Anisotropic behavior of Al1050 through accumulative roll bonding. *Materials*. 2021;14:6910. https://doi.org/10.3390/ma14226910

Information about the authors

Olesya D. Biryukova – Cand. Sci. (Eng.), Senior Research Scientist, Zhilyaev laboratory of mechanics of gradient nanomaterials, Nosov Magnitogorsk State Technical University (NMSTU).
https://orcid.org/0000-0002-3922-9289
E-mail: fimapatisonchik@inbox.ru

Anna E. Mogilnykh – Cand. Sci. (Eng.), Senior Research Scientist, Zhilyaev laboratory of mechanics of gradient nanomaterials, NMSTU.
https://orcid.org/0000-0002-0977-3566
E-mail: kozhemiakina.a@yandex.ru

Alexander M. Pesin – Dr. Sci. (Eng.), Chief Research Scientist, Zhilyaev laboratory of mechanics of gradient nanomaterials, NMSTU.
https://orcid.org/0000-0002-5443-423X
E-mail: pesin@bk.ru

Denis O. Pustovoytov – Cand. Sci. (Eng.), Leading Researcher, Zhilyaev laboratory of mechanics of gradient nanomaterials, NMSTU.
https://orcid.org/0000-0003-0496-0976
E-mail: pustovoitov_den@mail.ru

Ilya A. Pesin – Cand. Sci. (Eng.), Senior Research Scientist, Zhilyaev laboratory of mechanics of gradient nanomaterials, NMSTU.
E-mail: ilya33392@bk.ru

Maxim A. Biryukov – Leading Engineer, PJSC “Magnitogorsk Iron and Steel Works”.
E-mail: bigmax174@gmail.com

Информация об авторах

Олеся Дмитриевна Бирюкова – к.т.н., ст. науч. сотрудник, лаборатория «Механика градиентных наноматериалов им. А.П. Жиляева» Магнитогорского государственного технического университета (МГТУ) им. Г.И. Носова.
https://orcid.org/0000-0002-3922-9289
E-mail: fimapatisonchik@inbox.ru

Анна Евгеньевна Могильных – к.т.н., ст. науч. сотрудник, лаборатория «Механика градиентных наноматериалов им. А.П. Жиляева» МГТУ им. Г.И. Носова.
https://orcid.org/0000-0002-0977-3566
E-mail: kozhemiakina.a@yandex.ru

Александр Моисеевич Песин – д.т.н., гл. науч. сотрудник, лаборатория «Механика градиентных наноматериалов им. А.П. Жиляева» МГТУ им. Г.И. Носова.
https://orcid.org/0000-0002-5443-423X
E-mail: pesin@bk.ru

Денис Олегович Пустовойтов – к.т.н., вед. науч. сотрудник, лаборатория «Механика градиентных наноматериалов им. А.П. Жиляева» МГТУ им. Г.И. Носова.
https://orcid.org/0000-0003-0496-0976
E-mail: pustovoitov_den@mail.ru

Илья Александрович Песин – к.т.н., ст. науч. сотрудник, лаборатория «Механика градиентных наноматериалов им. А.П. Жиляева» МГТУ им. Г.И. Носова.
E-mail: ilya33392@bk.ru
Максим Александрович Бирюков – вед. инженер, ПАО «Магнитогорский металлургический комбинат».
E-mail: bigmax174@gmail.com

Contribution of the authors

O.D. Biryukova – defined the research aim, conducted experiments on accumulative roll bonding and thin-sheet rolling, participated in mechanical testing, analyzed and processed the results, and authored the article.

A.E. Mogilnykh – contributed to defining the research aim, performed experiments on thin-sheet rolling, participated in mechanical testing, and analyzed and processed the results.

A.M. Pesin – led the work on asymmetric rolling, defined the experimental methods, participated in conducting the asymmetric rolling experiments, and evaluated the results.

D.O. Pustovoytov – led the work on asymmetric rolling, defined the experimental methods, participated in conducting the asymmetric rolling experiments, and evaluated the results.

I.A. Pesin – participated in conducting the asymmetric rolling experiments and contributed to the discussion of the results.

M.A. Biryukov – contributed to the discussion of the results and participated in writing the article.

Вклад авторов

О.Д. Бирюкова – определение цели работы, проведение экспериментов по аккумулирующей и тонколистовой прокаткам, участие в проведении механических испытаний, оценка и обработка полученных результатов, написание статьи.

А.Е. Могильных – участие в определении цели работы, проведение экспериментов по тонколистовой прокатке, участие в проведении механических испытаний, оценка и обработка полученных результатов.

А.М. Песин – руководство работой по асимметричной прокатке, определение методик экспериментов, участие в проведении экспериментов по асимметричной прокатке, оценка полученных результатов.

Д.О. Пустовойтов – руководство работой по асимметричной прокатке, определение методик экспериментов, участие в проведении экспериментов по асимметричной прокатке, оценка полученных результатов.

И.А. Песин – участие в проведении экспериментов по асимметричной прокатке, участие в обсуждении результатов.

М.А. Бирюков – участие в обсуждении результатов, участие в написании статьи.

The article was submitted 28.03.2024, revised 03.04.2024, accepted for publication 07.05.2024

Статья поступила в редакцию 28.03.2024, доработана 03.04.2024, подписана в печать 07.05.2024