Experimental study of the effect of increasing technological plasticity during asymmetric rolling of aluminum alloys

Anna Kozhemyakina[1,a*], Alexander Pesin[1,b], Denis Pustovoytov[1,c], Leonid Nosov[1,d], Anna Baryshnikova[1,e], Natalia Lokotunina[1,f], and Dmitry Grachev[1,g]

[1] Nosov Magnitogorsk State Technical University, Laboratory of Mechanics of Gradient Nanomaterials named after A.P. Zhilyaev, 38 Lenin prospect, Magnitogorsk, 455000, Russian Federation

[a]kozhemiakina.a@yandex.ru, [b]pesin@bk.ru, [c]pustovoitov_den@mail.ru, [d]nosov.leopold@yandex.ru, [e]anyabar1999@mail.ru, [f]nml76@mail.ru, [g]omp_d.grachev@mail.ru

Keywords: Asymmetric Cold Rolling, High-Strength Steel Grades, Intermediate Annealing, Rolling Force, Laboratory and Industry Experiments

Abstract. In this paper the effect of asymmetric rolling on the possibility of increasing the technological plasticity of aluminum alloys was investigated. The experimental research was carried out on a laboratory asymmetric rolling mill with an individual drive of the work rolls with the possibility of creating a speed ratio from 1.0 to 5.0. It was shown that the increase of speed ratio of the work rolls from 1.0 to 5.0 significantly reduce the rolling force in comparison with symmetric rolling. Rolling force decreased in 1.9 times for alloy AD33 (AA6061), in 2.3 times for alloy AMg6, in 3.2 times for alloy D16 (AA2024). At the same time the technological plasticity was increased. Technological plasticity characterizes the ability of a material to undergo higher thickness reductions without fracture under certain conditions of stress, temperature, and strain rate. In asymmetric rolling the thickness reduction was increased from 48 to 87% for alloy D16, from 50 to 59% for alloy AMg6, and from 40 to 75% for alloy AD33 in comparison with symmetric rolling. In all cases the samples had initially room temperature and were subjected only to deformation heating and friction heating. Extremely high thickness reduction (87%) was achieved by a single pass asymmetric rolling (at speed ratio 5.0) for alloy D16. It was found that the ductility of the alloy D16 was 12.3% after asymmetric rolling with a thickness reduction of 87% and without the use of annealing. This was approximately 2 times higher than the initial ductility (6.2%) of the same alloy in the initial annealed state and much higher than ductility (0.3%) after symmetric rolling. New technological schemes of sheet rolling of aluminum alloys with high ductility and increased technological plasticity have been developed.

Introduction

Aluminum is one of main structural materials in the world, being second to only ferrous metals in production and consumption volumes. Now, Russia ranks as the world's second largest aluminum producer (after China) and the leading exporter of this metal [1].

One of main requirements for aluminum alloy sheets is technological plasticity or formability. Usually during rolling metals and alloys are hardened and, consequently, they show lower technological ductility [2]. Upon achievement of a definite level of deformation, technological plasticity is almost fully lost, and further deformation is not possible without additional heat treatment, followed, in turn, by complicating the process and reducing productivity, and introducing additional constraints of the process.

Since the 2010s, asymmetric rolling is seen in terms of forming the required properties of rolled products. Studies of Russian and foreign scientists [3-11] show that one of the most promising methods of obtaining the required properties of rolled products is an asymmetric thin sheet rolling process based on intentionally formed asymmetry due to the difference between peripheral speeds of work rolls.

However, the issues of increasing technological plasticity have not been properly studied; therefore, developing methods of improving technological plasticity of aluminum narrow strips during asymmetric rolling is still relevant.

The study is aimed at increasing technological plasticity of aluminum narrow strips by mismatching speeds of work rolls during asymmetric rolling.

Research methods and materials used. To carry out the studies, we selected aluminum alloys AMg6 and AD33, mostly used in the automotive industry, and alloy D16, highly used in all the industrial sectors, including aeronautical and transport engineering.

The experiments were conducted using asymmetric rolling of aluminum alloys, whose chemical composition is confirmed by the energy dispersive analysis:

- D16 (Si –0.26 %; Fe – 0.39 %; Cu – 4.00 %; Mn – 0.55 %; Mg – 1.48 %; Cr – 0.018 %; Zn – 0.16 %; Ti – 0.043 %; Ni – 0.030 %; B – 0.0018 %; Al – 93.09 %),
- AMg6 (Si – 0.17 %; Fe – 0.27 %; Cu – 0.045 %; Mn – 0.64 %; Mg – 6.15 %; Cr – 0.011 %; Zn – 0.027 %; Ti – 0.035 %; Ni – 0.008 %; Be – 0.0018 %; Al – 92.7 %),
- AS33 (Si – 0.58 %; Fe – 0.48 %; Cu – 0.22 %; Mn – 0.11 %; Mg – 0.80 %; Cr – 0.15 %; Zn – 0.080 %; Ti – 0.035 %; Be – 0.0014 %; Al – 97.45 %).

Research results. Basic data for simulating the process in DEFORM 2D/3D software: entry strip thickness h0 = 1.0-8.0 mm; initial temperature of the workpiece: 20 °C; work roll diameter R = 100-500 mm; friction is according to Coulomb's law; friction coefficient μ = 0.05-0.4; deformation ratio (reduction) ε = 10-90 %; bottom roll peripheral speed V_1 = 100 mm/s; roll speed ratio is from 1 to 5.

It has been found that during asymmetric rolling (V_1/V_2=5) of specimens of aluminum alloy AMg6 at reduction ε = 66 %, rolling force decreases from 610.0 to 192.2 kN as compared with symmetric rolling; torque on the bottom roll increases by 1.4 times, from 3.8 to 5.6 kN·m, and torque on the top roll decreases by 1.3 times, to 2.9 kN·m. Rolling force during asymmetric rolling decreases by 2.9 (reduction is 64 %, V_1/V_2=5) and 3.5 times (reduction is 87 %, V_1/V_2=5) for alloys AD33 and D16, respectively.

To carry out the experimental study, we used laboratory and industrial rolling mill 400 at the Zhilyaev Laboratory of Mechanics of Gradient Nanomaterials. Key specifications of the mill are given in Table 1 [12,13].

Table 1 – Specifications of the pilot and experimental laboratory two-high rolling mill

Parameter	Value
Type	Reversing two-high rolling mill with individually-driven work rolls
Screw-down mechanism	Hydraulic
Work roll diameter	340 [mm]
Work roll body length	400 [mm]
Rolling force (max)	2500 [kN] (250 [tf])
Torque (max)	2·65 [kN·m]
Main drive power	2·75 [kW]
Thickness of rolled sheet workpieces	50 [mm] – 0.5 [mm]
Materials to be rolled	Al, Fe, Ti, and other metals and alloys, having σ_T up to 1500 [MPa]
Applied technologies	– symmetric rolling, – asymmetric rolling, – cryogenic rolling, – accumulative roll bonding.
Total equipment weight	20 [t]

The experiments on mill 400 proved validity of the designed computer models in terms of force values. The calculated rolling torques on every work roll deviated from the measured values by 15 % or less.

The experimental results of rolling narrow strips from D16 with various work roll speed ratios are given in Table 2.

Table 2 – Rolling parameters of narrow strips from aluminum alloy D16

Sample No.	Thickness, mm		Relative reduction, [%]	Force, [kN]	Roll speed ratio	Hardness, [HB 5/125]	Note
	Entry thickness	Exit thickness					
23.09.2021 –9	6.00	3.10	48	463.80	5.0/5.0	104	Fracture of the sample
23.09.2021 –19 (3)	6.00	2.60	58	181.40	8.0/4.0	118	Fracture of the sample
23.09.2021 –41	6.00	2.00	67	215.10	9.0/3.0	86	Fracture of the sample
23.09.2021 –61	6.00	1.90	68	188.60	8.0/2.0	88	Fracture of the sample
23.09.2021 –92	6.00	0.90	85	243.00	10.0/2.0	73	No fracture of the sample
23.09.2021 –94	6.00	0.65	89	230.00	10.0/1.5	68	No fracture of the sample
23.09.2021 –95	6.00	-	-	-	10.0/1.3	-	The sample melted

The conducted experiments showed an increase in technological plasticity of aluminum narrow strips during asymmetric rolling. So, during conventional symmetric rolling (V1/V2 = 5.0/5.0) of aluminum alloy D16, in a single pass the sample was broken, when we tried to roll it to a thickness of 3.1 mm (reduction was 48 %). By increasing the work roll speed ratio up to V1/V2 = 10.0/2.0, we produced the aluminum narrow strip with a final thickness of 0.8 mm, relative reduction per pass was 87 %. A further increase in the work roll speed ratio up to V1/V2 = 10.0/1.5 contributed to producing the aluminum narrow strip with a final thickness of 0.65 mm (reduction was 89 %). The sample melted at a roll speed ratio of ≈ 7.7 (V1/V2=10.0/1.3).

Increased technological plasticity, when introducing asymmetry, was also experimentally confirmed for the samples of aluminum alloys AMg6, from 50 to 59%, and for AD33, from 40 to 75%.

The studies performed showed a decrease in rolling force with an increase in the work roll speed ratio. So, when rolling the samples of aluminum alloy D16 at work roll speed ratio V1/V2 = 10.0/2.0, force decreased by over 3.2 times (from 463.8 kN to 144.7 kN) at the degree of reduction corresponding to the degree of reduction in the symmetric mode.

A similar character of force reduction during asymmetric rolling was found for the samples of aluminum alloys AMg6 and AD33. So, when rolling the samples of aluminum alloy AD33, force decreased by 1.9 times (from 353.9 kN to 184.8 kN) at a reduction of 40%; when rolling the samples of aluminum alloy AMg6, force decreased by 2.3 times (from 290.0 kN to 125.5 kN) at a reduction of 50%.

For the first time, as a result of the experiments on rolling the samples from aluminum alloy D16, it was found that an increase in the work roll speed ratio by 1 – 5 times entailed an increase in the relative elongation of the samples after fracture. So, after asymmetric rolling, relative elongation after fracture increased from 6.2 to 12.3% (Table 3), while, in the symmetric case, it decreased from 6.2 to 0.3.

Table 3 – Mechanical properties of the narrow strips from alloy D16 after rolling

Sample	Ultimate tensile strength σ_B, [MPa]	Yield stress $\sigma_{0.2}$, [MPa]	$\sigma_{0.2} / \sigma_B$	Relative elongation, δ [%]
The sample after asymmetric rolling without lubrication (V_1/V_2 = 10.0/2.0; relative reduction per pass is 87 %)	283.6±1.3	234.4±1.1	0.83	12.3±0.13
The sample after asymmetric rolling with lubrication (V_1/V_2 = 10.0/2.0; relative reduction per pass is 85 %)	295.9±1.1	255.7±1.2	0.86	10.3±0.10
The sample after symmetric rolling	262.9±1.0	249.8±1.2	0.95	0.3±0.04
Original sample	191.7±0.9	141.4±0.8	0.74	6.2±0.08

Materials Research Proceedings **32** (2023) 309-316 https://doi.org/10.21741/9781644902615-36

It should be noted that during asymmetric rolling $\sigma_{0.2}/\sigma_B$ decreases by 13 % (from 0.95 to 0.83) as compared with symmetric rolling.

Developing process flow charts to increase technological plasticity of aluminum alloys D16, AMg6 and AD33 during asymmetric rolling.

The experiments conducted with symmetric rolling of aluminum alloy D16 showed a relative reduction of up to 45 %, keeping the produced narrow strip unbroken. In view of this, producing narrow strips from aluminum alloy D16, 0.65 mm thick, in compliance with GOST 13726-97, by conventional symmetric rolling, required four stages of rolling and four stages of annealing (Fig. 1) [14].

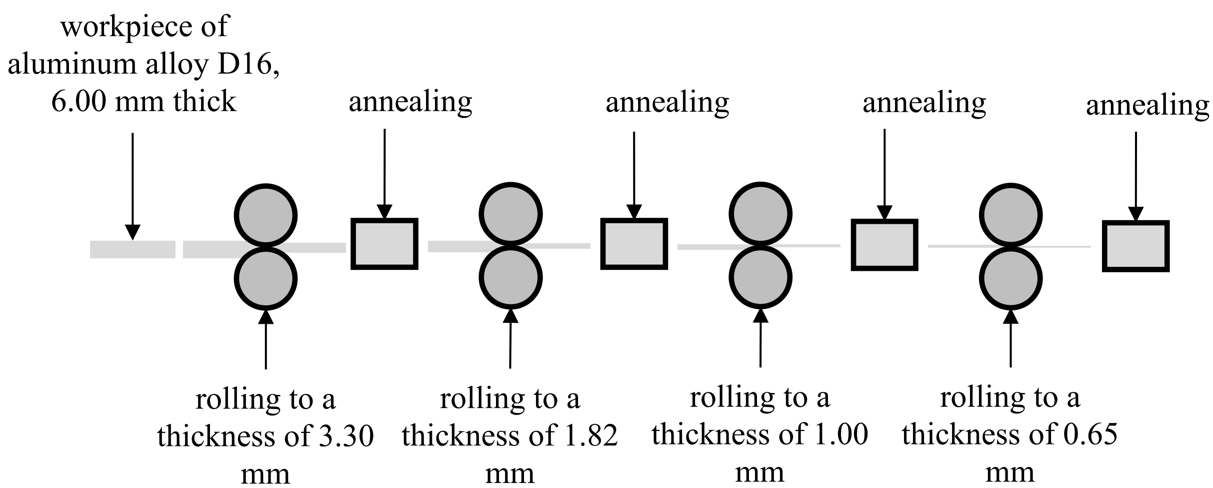

Fig. 1 – Process flow chart of symmetric rolling of the narrow strip from aluminum alloy D16

The above stated experimental data of rolling of the samples from aluminum alloy D16 with work roll speed ratio V_1/V_2 = 10.0/2.0 showed a potential increase in a single relative reduction up to 87 %, while keeping the narrow strip unbroken.

In this case, the conventional rolling process flow chart may be adjusted as stated in Fig.2.

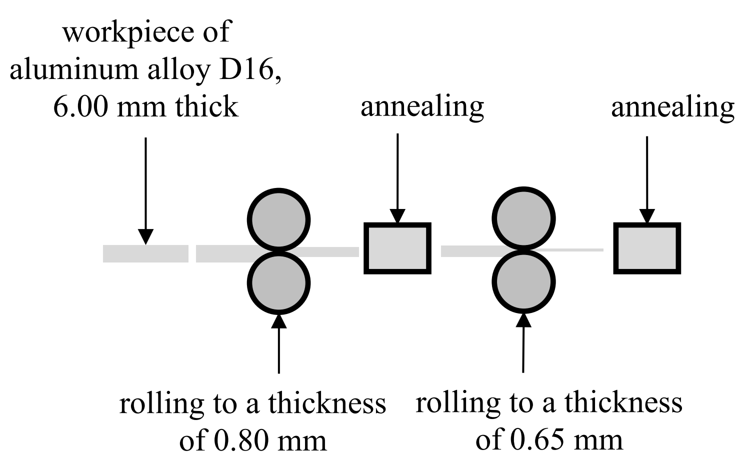

Fig. 2 – Process flow chart of asymmetric rolling of the narrow strip from aluminum alloy D16 with work roll speed ratio V_1/V_2 = 10.0/2.0

Materials Research Proceedings **32** (2023) 309-316 https://doi.org/10.21741/9781644902615-36

A further increase in the work roll speed ratio by 6.7 times (V_1/V_2 = 10.0/1.5) entail an increase in relative reduction per pass to 89 % (final thickness is 0.65 mm).

In this case, a process flow chart of asymmetric rolling of narrow strips from aluminum alloy D16 may be presented as in Fig. 3.

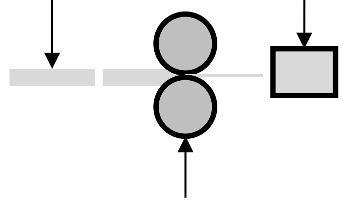

Fig. 3 – Process flow chart of asymmetric rolling of the narrow strip from aluminum alloy D16 with work roll speed ratio V_1/V_2 = 10.0/1.5

Similar process flow charts were developed for producing aluminum narrow strips from alloys AMg6 and AD33. The asymmetric rolling process flow chart for aluminum alloy AMg6 with work roll speed ratio V_1/V_2 = 10.0/2.0 contributes to excluding one rolling stage and annealing stage as compared with the conventional rolling sequence. Thus, by introducing asymmetry as a result of an increase in the work roll speed ratio up to 5, we can produce aluminum narrow strips from alloy AMg6, 0.78 mm thick, in a single pass.

The proposed process flow chart of rolling narrow strips from aluminum alloy AD33 at roll speed ratio V_1/V_2 = 8.0/2.0 shows that we can exclude three stages of rolling and three stages of annealing. Thus, the asymmetric rolling process flow chart for narrow strips from aluminum alloy AD33 at roll speed ratio V_1/V_2 = 8.0/2.0 can be used to produce aluminum narrow strips from alloy AD33, 0.50 mm thick, in a single pass.

Conclusion

The paper describes the approach developed at the Department of Materials Treatment Technologies at Nosov Magnitogorsk State Technical University and aimed at applying asymmetric rolling of metal narrow strips. In particular:

1) For the first time, it has been shown that an increase in the work roll speed ratio from 1.0 to 6.7 contributes to [15]:

- a significant decrease in rolling force as compared with symmetric rolling: by 1.9 times (for alloy AD33), by 2.3 times (for alloy AMg6), by 3.2 times (for alloy D16),
- higher technological plasticity (relative reduction increases without fracture of the samples) for D16 from 48 to 89 %, for AMg6 from 50 to 59 %, for AD33 from 40 to 75 %,
- increase in relative elongation of the samples to 12.3 % after asymmetric rolling of the narrow strip from alloy D16 as compared with 6.2 % in an annealed state.

2) The paper proposes new process flow charts for aluminum narrow strips of higher technological plasticity, excluding from one to three rolling stages and from one to three annealing stages.

Acknowledgment
The study was supported by a grant of the Russian Science Foundation (project No. 22-49-02041 dated 09.03.2022)

References

[1] Order of the Ministry of Industry and Trade of the Russian Federation No. 839 dated May 5, 2014 "On approval of the 2014 - 2020 and 2030 Strategy on Development of Ferrous Metallurgy in Russia and the 2014 - 2020 and 2030 Strategy on Development of Non-Ferrous Metallurgy in Russia". Information on https://www.garant.ru/products/ipo/prime/doc/70595824/#review

[2] V.N. Samokhvalov, Science of Metal Forming Processes, Samara University, Samara, 2019.

[3] V.M. Salganik, A.M. Pesin, Asymmetric Thin Sheet Rolling: Development of the Theory, Technologies and New Solutions, Moscow Institute of Steel and Alloys, Moscow, 1997.

[4] A.M. Pesin, D.O. Pustovoytov, O.D. Biryukova, A.E. Kozhemyakina, Asymmetric rolling of sheets and narrow strips: history and prospects for development, Bulletin of South Ural State University. Series: Metallurgy. 20 (3) (2020) 81-96.

[5] Y.H. Ji, J.J. Park, Development of severe plastic deformation by various asymmetric rolling processes, Materials Science and Engineering: A. 499 (1) (2009) 14-17. https://doi.org/10.1016/j.msea.2007.11.099

[6] Y.H. Ji, J.J. Park, W.J. Kim, Finite element analysis of severe deformation in Mg-3Al-1Zn sheets through differential-speed rolling with a high speed ratio, Materials Science and Engineering: A. 454 (2007) 570-574. https://doi.org/10.1016/j.msea.2006.11.076

[7] Q. Cui, K. Ohori, Grain refinement of high purity aluminum by asymmetric rolling, Materials Science and Technology. 16 (2000) 1095-1101. https://doi.org/10.1179/026708300101507019

[8] F.-Q. Zuo, J.-H. Jiang, A.-D. Shan, J.-M. Fang, X.-Yao Zhang, Shear deformation and grain refinement in pure Al by asymmetric rolling, Transactions of Nonferrous Metals Society of China. 18 (4) (2008) 774-777. https://doi.org/10.1016/S1003-6326(08)60133-8

[9] J. Jiang, Yi Ding, F. Zuo, A. Shan, Mechanical properties and microstructures of ultrafine-grained pure aluminum by asymmetric rolling, Scripta Materialia, 60 (10) (2009) 905-908. https://doi.org/10.1016/j.scriptamat.2009.02.016

[10] D.O. Pustovoytov, A.M. Pesin, A.A. Perekhozhikh, M.K. Sverdlik, Simulation of shear strain in a limit case of asymmetric thin sheet rolling, Vestnik of Nosov Magnitogorsk State Technical University, 1 (41) (2013) 65-68.

[11] D. Pustovoytov, A. Pesin, N. Lokotunina, A. Kozhemiakina, Influence of small microscopic grooves of work rolls on strain gradient induced in metal sheets during symmetric and asymmetric rolling, in: METAL 2019 - 28th International Conference on Metallurgy and Materials, Conference Proceedings, 2019, pp. 265-270. https://doi.org/10.37904/metal.2019.701

[12] Pustovoytov, D. Asymmetric (Hot, Warm,Cold, Cryo) Rolling of Light Alloys: A Review / D. Pustovoytov, A. Pesin, P. Tandon/ / Metals 2021. - 11 (956). - p. 1-46. https://doi.org/10.3390/met11060956

[13] O. Biryukova, A. Pesin, D. Pustovoytov, A. Kozhemiakina, L. Nosov, Obtaining laminated aluminum composites with a gradient structure based on asymmetric deformation, in: METAL 2021 - 30th Anniversary International Conference on Metallurgy and Materials, Conference Proceedings, 2021, pp. 496-501. https://doi.org/10.37904/metal.2021.4133

[14] A.M. Pesin, D.O. Pustovoytov, I.A. Pesin, A.E. Kozhemyakina, L.V. Nosov, A.I. Sverchkov, Developing asymmetric rolling process flow charts for aluminum narrow strips of higher strength and plasticity, Theory and Technology of Metallurgical Production, 2 (41) (2022) 32-42.

[15] Information on http://lmgn.magtu.ru/ru/oborudovanie.html