FEM SIMULATION AND ANALYSIS OF TEMPERATURE RISE DURING ASYMMETRIC CRYOROLLING OF ALUMINUM ALLOYS WITH A LARGE STRAIN

Denis PUSTOVOITOV [1], Alexander PESIN [1], Olesya BIRYUKOVA [1]

[1]*Nosov Magnitogorsk State Technical University, Magnitogorsk, Russian Federation,*
pustovoitov_den@mail.ru, pesin@bk.ru, fimapatisonchik@inbox.ru

Abstract

Asymmetric cryorolling is a technique that combines the features of asymmetric rolling and cryorolling, and can be used to produce ultrafine grained aluminum sheets. The problem with asymmetric cryorolling is the heat generated in the roll gap by high contact friction and the plastic deformation. Prediction of temperature rise during asymmetric cryorolling is very important. The temperature rise can be as large as to increase the sheet temperature above the cryogenic temperature. Therefore it is necessary to estimate the actual sheet temperature during asymmetric cryorolling for a precise control of recovery, and hence of the grain size. This paper presents the results of the finite element simulation of heat transfer during asymmetric cryorolling of aluminum alloys. The effects of thickness reduction (20 - 60 %), rolls speed ratio (0 - 60 %), friction coefficient (0.1 - 0.4), rolling velocity (0.05 - 10 m/s) and roll temperature (77 - 300 K) on the temperature rise in the strip during asymmetric cryorolling were found. The results of investigation can be useful for the development of the optimal treatment process of aluminum alloys by cryogenic severe plastic deformation to obtain the ultrafine grain structure and high strength properties.

Keywords: Asymmetric cryorolling, aluminum alloy, finite element method, temperature field, severe plastic deformation

1. INTRODUCTION

Conventional strengthening mechanisms applicable to aluminum alloys like solid solution strengthening, work hardening and precipitation hardening have their own limitations [1]. A possible way to further increase strength of aluminum alloys is to form an ultrafine grain (UFG) structure using severe plastic deformation (SPD) methods [2]. Cryorolling and asymmetric rolling are techniques that have potential application for large-scale industrial production of UFG aluminum alloys [3]. Cryorolling is a simple rolling process in which the cryogenic temperature is maintained by liquid nitrogen [4]. Deformation at cryogenic temperature is one of the main mechanisms leading to improvement in both strength and ductility of UFG aluminum alloys as well as narrow grain size distribution, bimodal structure, gradient structure [5]. The great advantages of cryorolling are the high accumulation of dislocations and the suppression of dynamic recovery in the processed material [6]. Asymmetric rolling is a process in which the speeds of the top and bottom rolls are different [7-10]. It is well known that shear strain plays a critical role in the grain refinement [10]. The great advantage of asymmetric rolling is a creation of additional high shear strain in the processed material. Asymmetric cryorolling is a technique that combines the advantages of cryorolling and asymmetric rolling, and can result in greater grain refinement compared to the other techniques [11]. The asymmetric cryorolling technique has been used successfully to produce UFG aluminum alloys. Yu et al. [11] carried out experiments on the asymmetric cryorolling process for Al 1050 and Al 6061 alloys in a multifunction rolling mill with of 50 mm diameter work roll under dry friction condition. For Al 1050, when the rolls speed ratio was 1.4, the grain size was about 211 nm [11]. The grain size of the processed material continuously decreases with increasing the applied shear strain. High shear strain through sheet thickness can be obtained by asymmetric cryorolling with the high thickness reduction per pass and high friction coefficient. However it leads to the problem with the heat generated in the roll gap. The temperature rise during the asymmetric cryorolling can be as large as to increase the sheet temperature above the cryogenic temperature. So the prediction of sheet temperature during asymmetric cryorolling is very important. There are only some experimental investigations on the microstructural evolution and the corresponding mechanical properties of aluminum alloys processed by asymmetric cryorolling. However, no research on finite element simulation of asymmetric cryorolling has been found. The goal of this paper is the finite element simulation and analysis of the temperature rise during asymmetric cryorolling of Al 1100, Al 5083 and Al 6061-T6 alloys. The results of investigation can be useful for the development of the optimal treatment process of aluminum alloys by cryogenic SPD to obtain the UFG structure and high strength properties.

2. RESEARCH METHOD

A coupled deformation and heat transfer simulation of the asymmetric cryorolling was carried out using the commercial FEM code DEFORM 2D. The governing equation (1) for heat transfer is expressed as [12]:

$$k\nabla^2 T + \dot{q} = \rho C \frac{\partial T}{\partial t} \tag{1}$$

where:

ρ - density (kg/m^3)

C - specific heat capacity (J/(kg·K))

T - temperature (K)

k - thermal conductivity (W/(m·K))

$\dot{q}$ - heat generation term

Heat generation due to plastic deformation is given by equation (2) [12]:

$$\dot{q}_{pw} = 0.9\int \overline{\sigma}\dot{\overline{\varepsilon}}\, dV \tag{2}$$

where:

$\overline{\sigma}$ - flow stress (MPa)

$\dot{\overline{\varepsilon}}$ - strain rate (s^{-1})

The boundary condition for the roll-strip contact surface includes friction heating and heat exchange via temperature difference of two objects in accordance with equation (3) [12]:

$$\dot{q}_1 = \int_{S_1} 0.9 f_{S_1} \left|u_{S_1}\right| dS_1 + \int_{S_1} H \Delta T dS_1 \tag{3}$$

where:

u_{S_1} - sliding velocity (m/s)

f_{S_1} - friction stress (MPa)

H - lubricant heat transfer coefficient (N/(K·s·mm))

ΔT - temperature difference between two objects (K)

The boundary condition of the free surface includes convection heat and radiation heat from/to the environment in accordance with equation (4) [12]:

$$\dot{q}_2 = \int_{S_2} h_c \left(T - T_\infty\right) dS_2 + \int_{S_2} \sigma\xi \left(T^4 - T_\infty^4\right) dS_2 \tag{4}$$

where:

h_c - convection heat transfer coefficient (N/(K·s·mm))

T_∞ - environment temperature (K)

σ - Stefan-Boltzmann radiation constant (W·m^{-2}·K^{-4})

ξ - emissivity of the surface

The geometry model and FE meshing of asymmetric cryorolling process are shown in **Figure 1**. The diameters of the rolls were 300 mm, and the rolls were considered as rigid. Bottom roll was faster in all calculation variants. A Coulomb friction model was used between rolls and strip. High-carbon chromium alloy steel AISI D2 from DEFORM 2D material library was chosen as a material for rolls. Rolls were meshed with ≈ 10000 brick elements. Strip with initial thickness of 1.0 mm was used for all simulations. The number of initial brick elements was ≈ 2000 for the strip. Process simulation was performed at temperature of liquid nitrogen (77 K) with taking into account the increment of the metal's temperature due to the conversion of mechanical work into heat through sliding on contact surfaces and plastic deformation. The initial temperature of the strip was 77 K. Al 1100, Al 5083 and Al 6061-T6 alloys were chosen as a hardened rigid-plastic materials for the strip. The stress-strain curves of the materials at the temperature range 77 - 300 K are shown in **Figure 2**. The stress-strain curves for 300 K were used from DEFORM 2D material library. The stress-strain curves for 77 K were approximated with using data from [13]. The thermal constants of materials used in FEM simulation are shown in **Table 1**. **Figure 3** graphically shows the thermal conductivity and specific heat of aluminum alloys at temperature below 300 K [14].

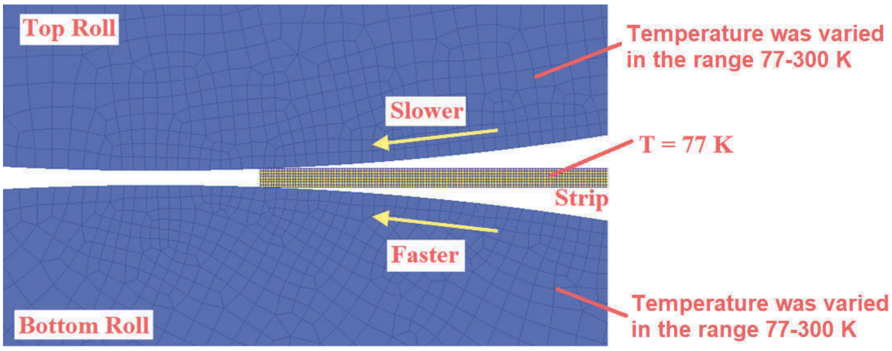

Figure 1 Geometry model and FE meshing of asymmetric cryorolling process

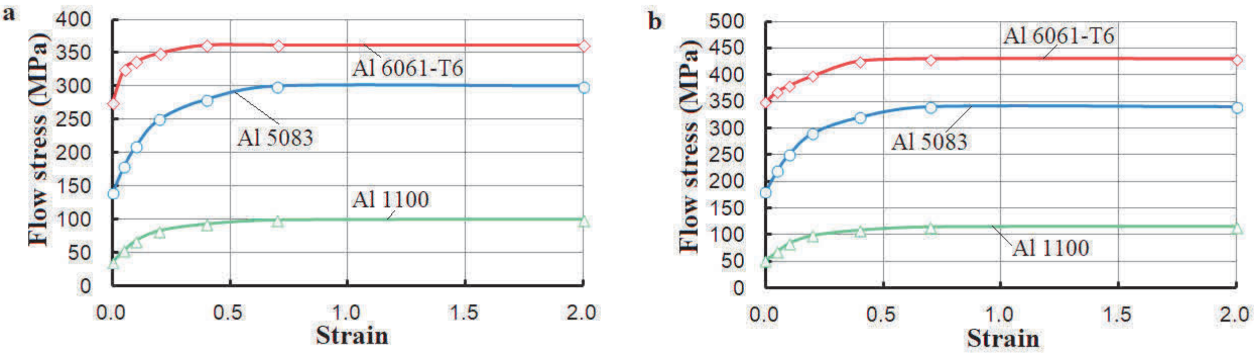

Figure 2 Stress-strain curves of aluminum alloys at 300 K (a) and 77 K (b)

Table 1 Thermal constants of materials used in FEM simulations

Parameter	Material	
	Al 1100, Al 5083, Al 6061-T6	AISI D2
Thermal conductivity (W/(m·K))	See **Figure 3a**	50.7 at 77 - 300 K
Emissivity	0.050 at 300 K 0.023 at 77 K	0.7 at 77 - 300 K
Specific heat (J/(kg·K))	See **Figure 3b**	484 at 77 - 300 K
Heat transfer coefficient between rolls and sheet (N/(K·s·mm))	11	11
Heat transfer coefficient between rolls/strip and air (N/(K·s·mm))	0.02	0.02
Environmental temperature (K)	300	300

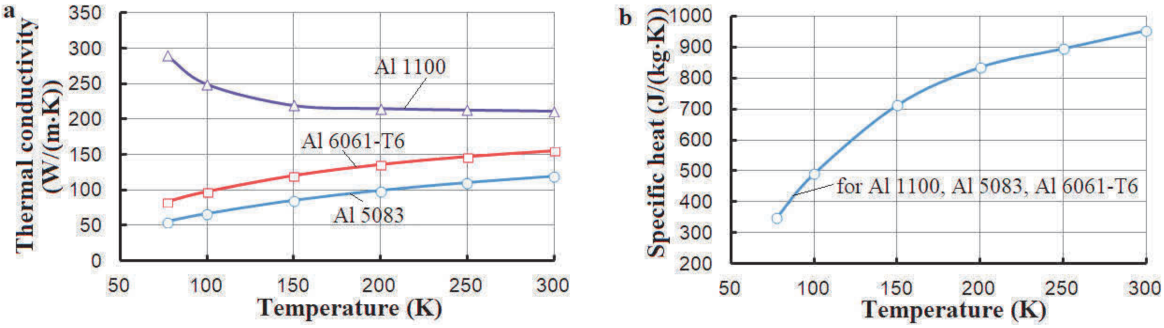

Figure 3 Thermal conductivity (a) and specific heat (b) of aluminum alloys at temperature below 300 K

In the simulations, the influences of thickness reduction ε (20 - 60 %), rolls speed ratio (0 - 60 %), friction coefficient *f* (0.1 - 0.4), rolling velocity (0.05 - 10 m/s) and roll temperature (77 - 300 K) on the temperature rise in the strip during asymmetric cryorolling were analysed.

3. SIMULATION RESULTS AND DISCUSSION

The temperature rise T_R was considered as the difference between final mean temperature of the strip at the exit plane of the deformation zone and the initial strip temperature 77 K in accordance with equation (5):

$$T_R = \left(\sum_{i=1}^{6} T_{Pi} / 6 \right) - 77 \qquad (5)$$

where:

T_{Pi} - temperature (K) of point i (i = 1 - 6, see **Figure 4**)

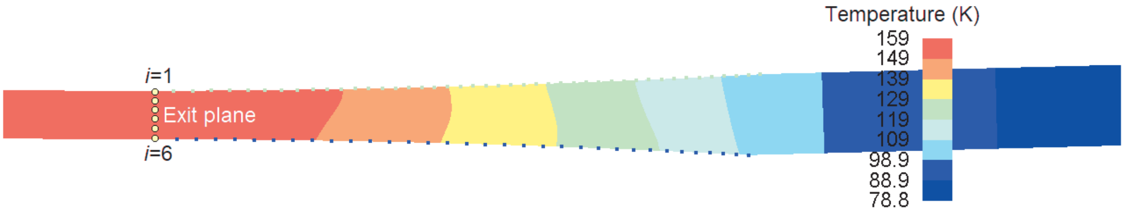

Figure 4 Temperature field and selected points at exit plane of deformation zone (Al 1100, ε = 40 %, *f* = 0.4, rolls speed ratio 35 %, roll temperature 77 K, rolling velocity 0.1 m/s)

For maintaining the cryogenic conditions the temperature of the strip during asymmetric cryorolling is required to be in the range from 77 K to 173 K (from -196 °C to -100 °C) [11]. So the temperature rise should not exceed 96 K. **Figures 5-7** show the influence of the rolls speed ratio on the temperature rise and the effective strain depending on different thickness reductions. In all cases: material is Al 1100, friction coefficient is 0.4, rolls speed ratio is 35 %, roll temperature is 300 K, rolling velocity is 0.1 m/s. During asymmetric cryorolling with thickness reduction ε = 60 % the increasing the rolls speed ratio up to 55 % leads to serious increasing of the effective strain from *e* ≈ 1.5 to *e* ≈ 4.1 (**Figure 5**). The non-linear effect of the influence of the rolls speed ratio was found. At first the effective strain is increased to the maximum value *e* ≈ 4.1 with increasing of the rolls speed ratio up to 55 %, but after that the effective strain is sharply decreased to *e* ≈ 2 (**Figure 5**). Changing of temperature rise has the opposite tendency. With increasing the rolls speed ratio up to 60 % the temperature rise is decreased from 335 K to 283 K. It can be explained by serious decreasing of friction stresses acted in the deformation zone during asymmetric cryorolling. However the large strain does not provide cryogenic rolling conditions. With decreasing the thickness reduction the temperature rise is also decreased from the range T_R = 283 - 335 K at ε = 60 % to the range T_R = 117 - 124 K at ε = 20 % (**Figure 7**). It can be explained by decreasing of heat generation due to work of plastic deformation. Contact friction is one of the main factors that affect the shear strain during asymmetric cryorolling. High friction coefficient increases the opposite contact friction forces which operates in the deformation zone and it creates an additional shear strain. **Figure 8** shows the influence of friction coefficient on temperature rise and effective strain when thickness reduction is 40 %, rolls speed ratio is 35 %, roll temperature is 300 K, rolling velocity is 0.1 m/s. With increasing the friction coefficient from 0.1 to 0.4 the temperature rise is also increased from 165 K to 201 K. It can be explained by additional friction heating. **Figure 9** shows the influence of roll temperature and rolling velocity on temperature rise during asymmetric cryorolling when thickness reduction is 40 %, rolls speed ratio is 35 % and friction coefficient is 0.4. Decreasing of roll temperature from 300 K to 77 K is effective when rolling velocity is very low, e.g. 0.05 m/s. In this case temperature rise is decreased from 210 K to 55 K (**Figure 9**). Influence of rolls speed ratio on temperature rise depending on properties of aluminum alloys is shown in **Figure 10**. With increasing the strength of the aluminum alloy the temperature rise is also increased because of additional heat generation due to work of plastic deformation.

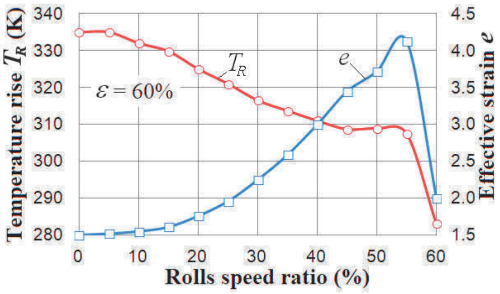

Figure 5 Influence of rolls speed ratio on temperature rise T_R and effective strain (ε = 60 %)

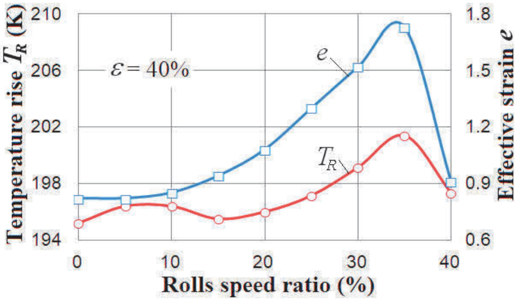

Figure 6 Influence of rolls speed ratio on temperature rise T_R and effective strain (ε = 40 %)

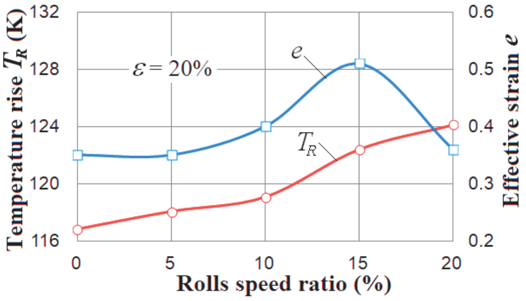

Figure 7 Influence of rolls speed ratio on temperature rise T_R and effective strain (ε = 20 %)

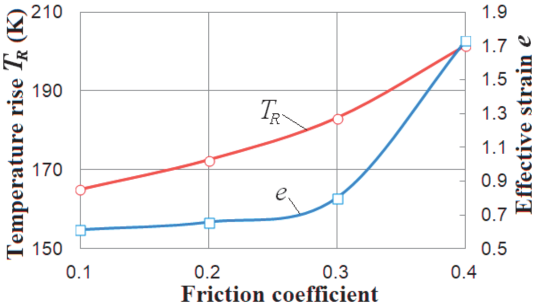

Figure 8 Influence of friction coefficient on temperature rise T_R and effective strain (ε = 40 %)

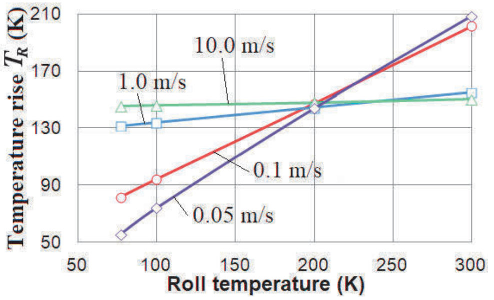

Figure 9 Influence of roll temperature and rolling velocity on temperature rise

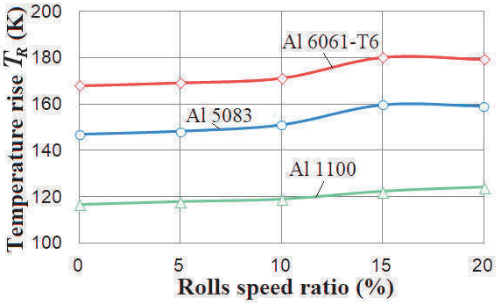

Figure 10 Influence of rolls speed ratio on temperature rise for different aluminum alloys

4. CONCLUSION

Asymmetric cryorolling with high thickness reduction per pass, high rolls speed ratio and high friction coefficient leads to serious increase of the effective strain up to mode of SPD when $e \geq 1.0$. However it leads to temperature rise of the strip above the cryogenic temperature. Effective strain can be extremely high ($e \approx 4.1$) during asymmetric cryorolling with thickness reduction ε = 60 % and the rolls speed ratio of 55 %. However the temperature rise exceeds 300 K in this case and the cryogenic conditions are not provided. Cryogenic conditions when the strip temperature is maintained in the range from 77 K to 173 K during asymmetric cryorolling of aluminum alloys with a large strain ($e \geq 1.0$) can be obtained with decreasing of roll temperature from 300 K to 77 K and with decreasing of rolling velocity from 1.0 - 10.0 m/s to 0.05 - 0.1 m/s or lower. However the main disadvantage of the low rolling velocity is the low productivity of the asymmetric cryorolling process. Low strength aluminum alloys (e.g. Al 1100) can be processed with high thickness reductions per pass (up to 40 %). Medium and high strength aluminum alloys (e.g. Al 5083 and Al 6061-T6) should be processed with the decreased thickness reductions per pass (e.g. no more than 20 %). The results of investigation can be useful for the development of the optimal treatment process of aluminum alloys by cryogenic SPD to obtain the ultrafine grain structure and high strength properties.

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