Chapter 5

Differential Speed Rolling: A New Method for a Fabrication of Metallic Sheets with Enhanced Mechanical Properties

Wojciech Polkowski

Additional information is available at the end of the chapter

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Abstract

This chapter presents an actual progress in the usage of a new processing method called differential speed rolling (DSR) to a fabrication of metallic sheet materials with enhanced mechanical properties. An introduction of the rolls speed differentiation to a rolling process results with qualitative and quantitative changes of imposed strain and thus to new structural effects as compared to a conventional rolling. The presence of additional high through-thickness shear strain in the DSR technique is utilized to a substantial grain refinement (to a fabrication of high-strength ultrafine-grained materials) and therefore is regarded as one of the severe plastic deformation (SPD) methods. In this chapter, mechanical properties of selected DSRed metals are compared to those of their counterparts processed by competitive hydrostatic SPD methods. Moreover, the imposed complex strain state in the DSR method significantly affects a crystallographic texture of fabricated sheet materials leading to more favorable anisotropic characteristics and to an improved formability that is especially important in the case of aluminum and magnesium alloys.

Keywords: Sheet forming, Ultrafine-grained materials, Severe plastic deformation, Differential speed rolling, Formability

1. Introduction

A fabrication of high-strength metals and alloys is an emerging field of materials science and engineering originating from continuously increased demands of industry, leading to a formation of linkage between various aspects of mechanical metallurgy, the physics or material's mechanics.

According to a well-known Hall-Petch relationship, a grain refinement through a properly conducted thermomechanical processing is one of the most efficient ways to improve a mechanical strength of metallic materials. It has been already established that the best compromise between a high-strength and an acceptable ductility is generally achieved when a grain size is in the submicron (ultrafine) regime of 100–1,000 nm. Furthermore, a large fraction of high-angle grain boundaries (HAGBs) in a material's volume is a crucial feature supporting a kinetics of diffusion-related phenomena and resulting with, e.g., an improved environmental resistance of ultrafine-grained (UFG) materials, as compared to their counterparts with a coarse-grained structure. Processing methods involving a severe plastic deformation (SPD) have been already recognized as the most efficient and thus industrially preferable techniques of the UFG material fabrication. In SPD processes, the material is subjected to a very large plastic deformation (true strain ε is even greater than 80) usually being conducted under a hydrostatic pressure and room temperature conditions. As a consequence of the imposed intense plastic straining, a mechanical fragmentation of material grains by introducing a number of mutually intersected shear bands or a formation of fine-grained structure due to an activation of structure restoration processes (i.e., a dynamic or post-dynamic recovery and recrystallization) takes place. So far, a number of hydrostatic SPD methods such as cyclic extrusion compression (CEC), equal-channel angular pressing (ECAP), and high-pressure torsion (HPT) have been developed and implemented. However, despite of a successful fabrication of various UFG materials, these SPD methods also exhibit some serious disadvantages, e.g., a poor process efficiency, small dimensions of produced (semi-) products, or a necessity of using specialized machines and tools. Therefore, a development of SPD methods that are based on highly efficient, continuous plastic deformation processes conducted on widely available conventional processing devices has generated a considerable research interest.

2. Differential speed rolling (DSR): a new continuous severe plastic deformation method

A differential speed rolling (DSR) is a modification of the rolling process which involves a deformation with different values of a rotational speed of the upper and the lower rolls. This kind of processing belongs to the group of asymmetric rolling processes that have been already introduced to a large-scale production of flat steel products [1]. The asymmetry is introduced to the rolling process by using different diameters, different materials (that generate a differentiation of friction conditions on upper and lower surface of a deformed sample), or different rotational speed of working rolls (**Figure 1**). From a standpoint of design simplicity, the easiest and the best solution is the differentiation of rolls speed. In the case of the DSR process, this modification gives an unequal rolling velocity imposed to upper and lower surface of the processed sample. The main characteristic of the DSR method is a value of a rolls speed differentiation coefficient R defined as a ratio of the upper to lower rolls speed.

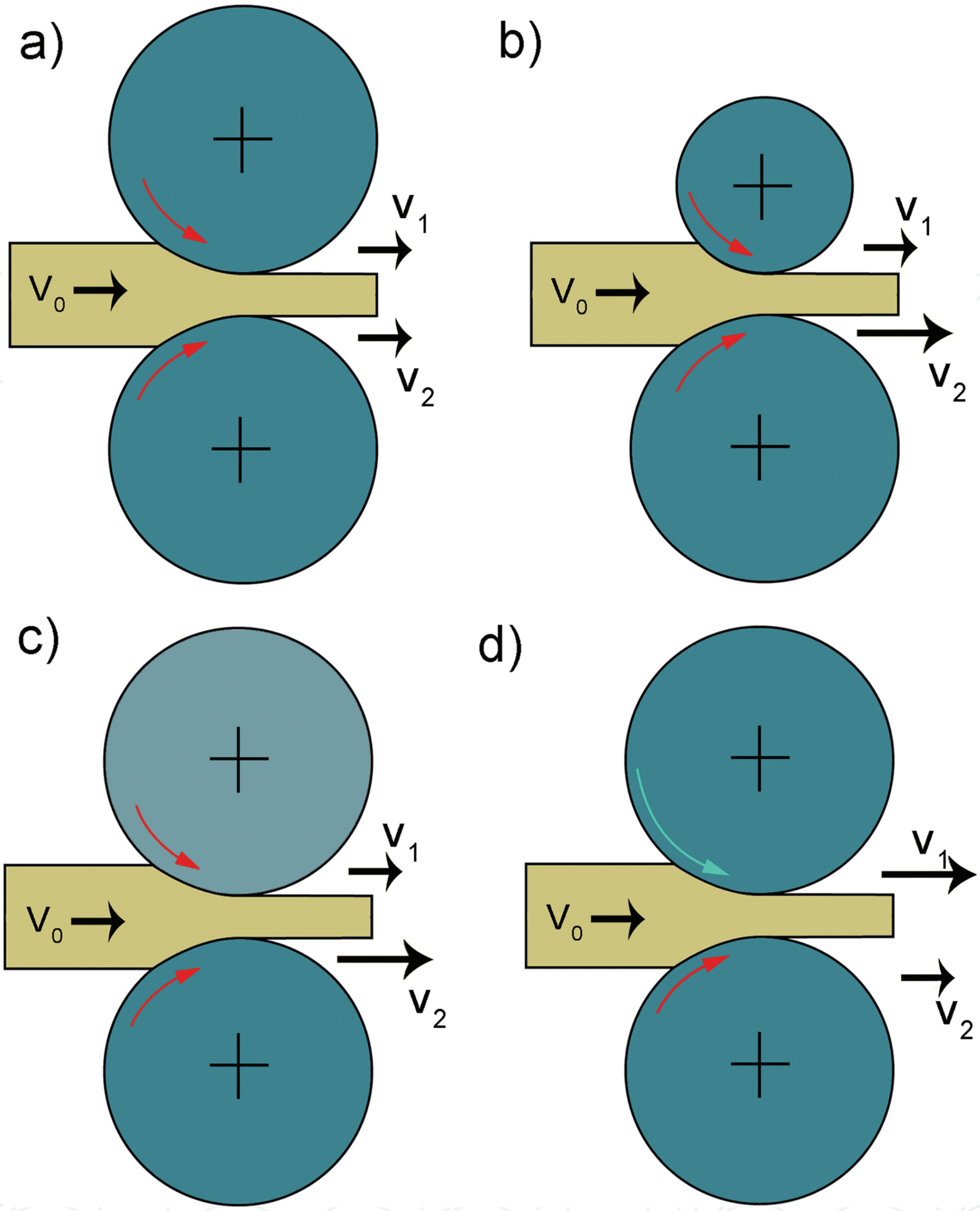

Figure 1. A schematic drawing of (a) a normal rolling process and different variants of the asymmetric rolling (b) with an unequal rolls diameter (differential diameter rolling), (c) with a different rolls materials (a differential friction rolling), and (d) with a differential speed rolling.

The first theoretical description of such a process was proposed in the 1940s of the last century [2], and a further development of this method was mainly devoted to the improvement of technological aspects of the rolling process. Between 1960s and 1980s, many experiments and theoretical calculations have been carried out on the roll forces, roll torques, and rolled product shape alteration due to the existed asymmetry of rolling gap [3–6]. It has been generally established that the asymmetry of the roll gap may be utilized as a factor improving work of the hydraulic gauge control in a plate-rolling mill leading to, e.g., a prominent decrease of the rolling force and torque and improvement of a rolled strip shape. Additionally, a lower rolling force and torque are not only beneficial in terms of providing a lower wearing of tools and a higher rigidity of the rolling cage but also give a better control and make a process more applicable to produce thin sheets or foils [7]. It was shown by Dyja et al. [8] on the real example of a plate mill in the steel plant, Częstochowa (Poland), that the introduction of rolls speed asymmetry to the rolling of eight different carbon-manganese steels leads to decreasing of the rolling force in the last finishing passes up to more than 70 %, depending on the applied process parameters. It has been documented that the implementation of asymmetrical rolling in the rolling mills equipped with the hydraulically controlled adjustment of rolling gap results with an improvement of plate geometry, e.g., a flatness and transverse profile or decrease of the thickness differentiation along the plate. These results are in line with those presented by Kawalek et al. [9] indicating that a lower value of the unit press decreases an elastic deflection of a rolling stand upon an asymmetric rolling pass.

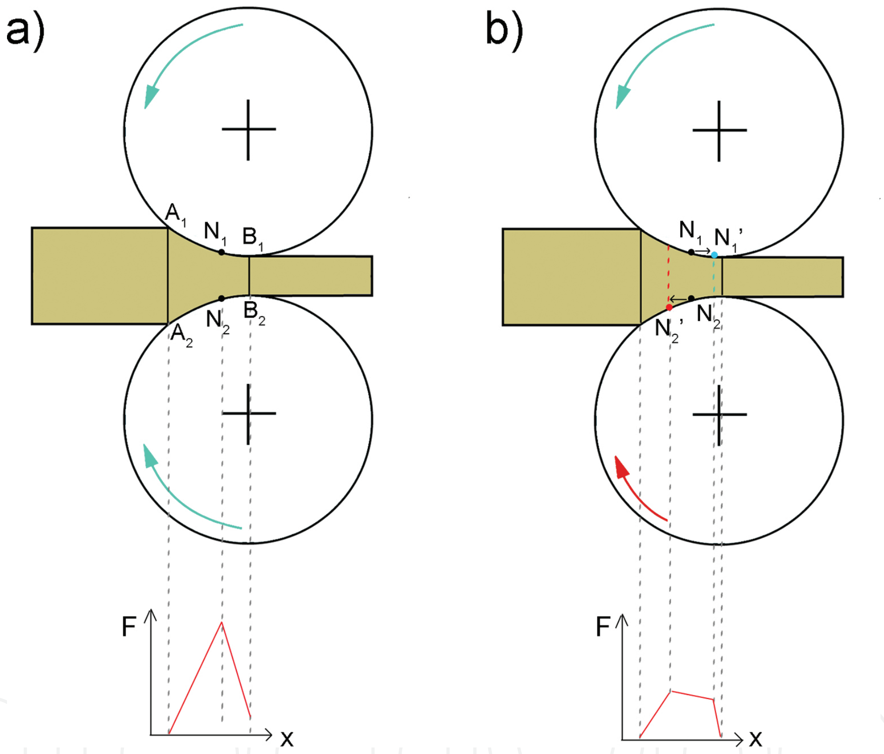

Figure 2. A rolling gap geometry in (a) the equal speed rolling and (b) the differential speed rolling. In the case of the DSR process, a shear zone is located between neutral points (N1′:N2′) shifted to different positions (based on [10]).

This positive effect of the DSR implementation on technological aspects of a rolling process is attributed to a change in the deformation geometry. Roumina and Sinclair [10] reported that the differentiation of rolls speed results with a shifting of so-called neutral points (the position where the sheet velocity equals the roll velocity) on upper and lower surfaces of the sample. The neutral point associated with the slow roll is shifted toward the entrance of the roll gap, while the neutral point associated with the fast roll is moved toward the exit of the roll gap (**Figure 2**). This situation leads to both a different distribution of rolling pressure (and thus lowering of the rolling force) and an imposition of a high through-thickness shear strain to the material. It was also confirmed by Tian et al. [11] that the extent of cross shear region increases with the increase of the speed ratio, whereas the rolling force decreases.

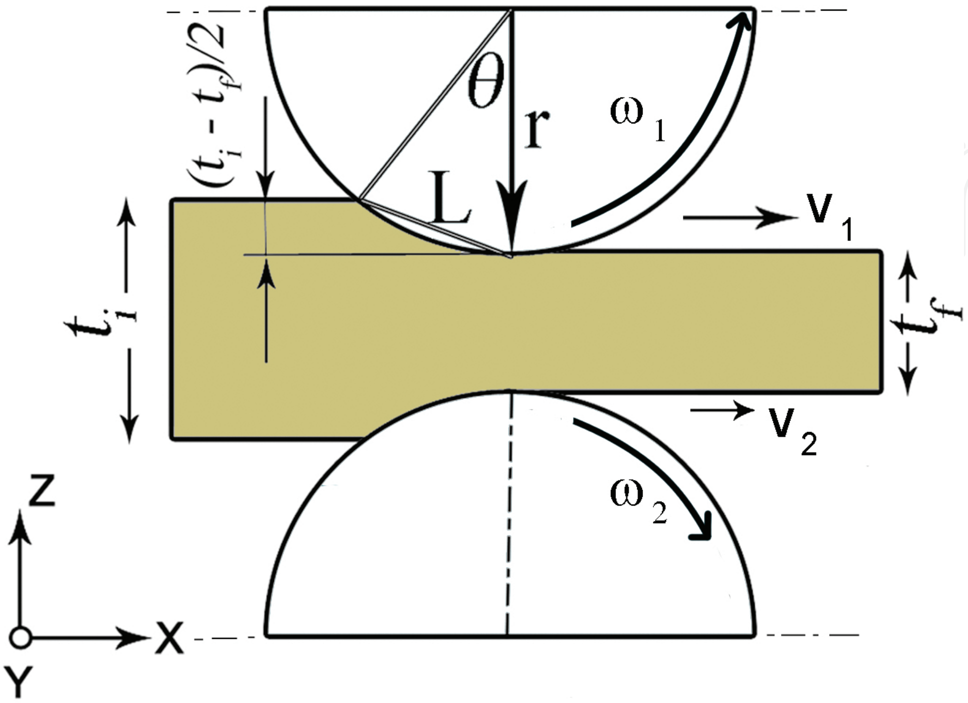

Figure 3. A schematic drawing that is used for strain and strain rate assessment in the DSR process (based on [12]).

Based on the assumption that the deformation gradient in the DSR method is approximated by a superposition of a plane strain (which is specific for the normal rolling process) and a simple shear in the rolling direction (Eq. (1)), Ko et al. [12] proposed approximate equations for the strain and strain rate imposed by DSR (Eq. (6)). This evaluation is based on trigonometric relationships between a geometry of a sample and a rolling gap schematically shown in **Figure 3**. However, it is worth noted that in this attempt the friction between a sample and the rolls is neglected; thus, calculated strain values may be underestimated:

$$\begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{zz} = -\varepsilon_{xx} \end{bmatrix} + \begin{bmatrix} 0 & 0 & \varepsilon_{xz} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx} & 0 & \varepsilon_{xz} \\ 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{zz} = -\varepsilon_{xx} \end{bmatrix} \tag{1}$$

By taking into assumption that θ is a central arc angle defined by positions of inlet and outlet points of the rolling gap, t_i and t_f are an initial and a final thickness of the sample, and r is the rolls radius, the following calculation procedure has been proposed.

The θ value may be calculated by using an assumption that for satisfied contact conditions the angle value is closed to its sinus, so

$$\sin\theta \approx \theta = \frac{\sqrt{r\left(t_i - t_f\right) - \left(\frac{t_i - t_f}{2}\right)^2}}{r} \tag{2}$$

Therefore, the contact arc length L is equal to

$$L = r \times \theta = r \times \frac{\sqrt{r\left(t_i - t_f\right) - \left(\frac{t_i - t_f}{2}\right)^2}}{r} = \sqrt{r\left(t_i - t_f\right) - \left(\frac{t_i - t_f}{2}\right)^2} \tag{3}$$

Subsequently, the average deformation time t_{ave} is calculated as follows:

$$t_{ave} = \frac{L}{v_{ave}} \tag{4}$$

where v_{ave} is an average rolls velocity. By having calculated the t_{ave} value, the simple shear component ε_{xz} may be defined as

$$\varepsilon_{xz} = \left(\frac{\left(v_G - v_D\right) \cdot t_{ave}}{\left(\frac{t_i + t_f}{2}\right)} \right) \cdot 1/2 \tag{5}$$

Finally, the total equivalent strain is expressed as

$$\varepsilon = \frac{2}{\sqrt{3}} \cdot \sqrt{\left(\varepsilon_{xx}^2 + \varepsilon_{xz}^2\right)} \tag{6}$$

where ε_{xx} is a true logarithmic strain equal to $\ln(t_f/t_i)$.

It should be underlined that in the "technological" attempt to the DSR process, the introduced asymmetry is rather low (usually the R value is not greater than 1.2) and thus is treated as a "correction coefficient," whereas, since the end of 1990s, a new growing direction in the research on the DSR process has been started. In these years, first works on a possible utilization of a shear deformation imposed upon the DSR process to control a microstructure and property evolution of various engineering materials were published [13, 14] starting a "material approach" to this subject. While the shear strain is found to be proportional to the rolls speed mismatch, it is assumed that extensive microstructure changes need both a large deformation and a high ratio of rolls speed asymmetry (the R values are usually higher than 2).

Generally, there are two main purposes for using the DSR method in a material processing. The first one is to produce high-strength materials by a grain refinement through a high-plastic strain accumulation—due to the presence of additional shear deformation, the DSR method is considered as one of the SPD techniques. The second one is to control a deformation texture that affects anisotropy of mechanical properties (and also determines a recrystallization texture formed upon a subsequent annealing). Obviously, these two purposes are in many cases simultaneously achieved.

Material	Processing		UTS [MPa]	Reference
Pure copper	ECAP (1 cycle)		344	[16]
	ECAP (4 cycles)		413	[17]
	ECAP (8 cycles)		378	[18]
	ECAP (8 cycles)		386	[19]
	HPT (5 cycles)		445	[20]
	ARB	(1 cycle)	290	[21]
		(2 cycles)	350	
		(3 cycles)	370	
		(4 cycles)	380	
		(5 cycles)	388	
		(6 cycles)	395	
	As-annealed		200	[15]
	Equal speed rolling (1-pass reduction of 65 %)		350	
	DSR (R = 3, 1-pass reduction of 65 %)		**470**	

Table 1. A comparison of ultimate tensile strength (UTS) of pure copper processed by various SPD methods, an equal speed rolling and the DSR technique.

The grain refinement effect by the DSR method was previously observed in numerous pure metals and alloys. Kim et al. [15] reported that in oxygen-free copper, submicron grain size of 820 nm is obtained after the 65 % thickness reduction in a single rolling pass by the DSR method (the R = 3). This processing also leads to a formation of a large fraction of high-angle grain boundaries (HAGBs) (~60 %) and maintaining a high electrical conductivity (that proves a low level of structure defects). Furthermore, reported results of tensile tests show that the DSR-deformed copper exhibits a superior ultimate tensile strength (UTS) than that of copper subjected to the equal speed rolling, accumulative roll bonding (ARB), or hydrostatic SPD methods (the HPT and an equal-channel angular pressing (ECAP)) (**Table 1**). These results clearly point toward a high efficiency of the DSR process—prominently higher strength than in the case of other competitive processing methods in a large bulk material is achieved in one simple operation.

Similar findings were shown by Jiang et al. [22] on pure aluminum subjected to the DSR process. The authors found that the cold rolling (with the $R = 3$) of commercially pure aluminum to 90 % of thickness reduction leads to a formation of microstructure composed of submicron-equiaxed grains and a high fraction of HAGBs (~50 %). As in the case of the copper, the DSR-processed pure aluminum exhibits a higher strength than that processed by a normal rolling and competitive SPD-based fabrication methods (**Table 2**), confirming a superiority of this process over hydrostatic techniques.

Material	Processing		UTS [MPa]	Reference
Commercially pure aluminum	ECAP	(1 cycle)	120	[23]
		(2 cycles)	130	
	ECAP	(1 cycle)	110	[24]
		(2 cycles)	135	
		(8 cycles)	165	
	Repetitive tube expansion and shrinking (RTES) (1 cycle)		140	[25]
	Rotatory swaging (1 cycle—true reduction of 3)		163	[26]
	Constrained groove pressing (CGP) (2 cycles)		105	[27]
	HPT (2 cycles)		145 (estimated from reported hardness)	[28]
	Equal speed rolling (total thickness reduction of 90 %)		150	[22]
	DSR (R = 3, total thickness reduction of 90 %)		**250**	

Table 2. A comparison of ultimate tensile strength (UTS) of commercially pure aluminum processed by various SPD methods, an equal speed rolling and the DSR technique.

Some works were also devoted to a fabrication of high-strength sheets made of ultrafine-grained titanium via the DSR process. Kim et al. [29] documented that this purpose may be successfully achieved by an effective grain refinement (the grain size in the range of 100–300 nm) through the differential speed rolling (with the $R = 3$) to 63 % of the thickness reduction obtained in one single rolling pass at room temperature. Consequently, as-received titanium was characterized by the UTS of 895–915 MPa, which is a better result than that represented by pure Ti processed by other SPD methods (**Table 3**). Moreover, the same authors showed in the further work [30] that a microstructure state formed upon the proposed DSR processing ensures an enhanced corrosion resistance in acid environments (H_2SO_4 and HCl solutions) by altering growth kinetics of passivating oxide film. Since a formation of continuous, passive surface layer is a key factor in a biomedical usage of titanium, the DSR method shows a good usefulness in the field of various human healthcare applications.

Material	Processing		UTS [MPa]	Reference
Commercially pure titanium	ECAP (1 cycle)		780	[31]
	ECAP	1 cycle	571	[32]
		3 cycles	624	
		5 cycles	665	
	ARB (6 cycles)		892	[33]
	HPT (4 cycles)		870	[34]
	DSR (R = 3, 1-pass reduction of 63 %)		**895–915**	[29]

Table 3. A comparison of ultimate tensile strength (UTS) of commercially pure titanium processed by various SPD methods and the DSR technique.

The strengthening of metals upon the DSR deformation is related to the structure refinement by a formation of narrowly spaced shear bands distributed homogeneously over the entire section of the sheet and a high temperature rise during the rolling. It was presented by Kim et al. [15] that the temperature rise may exceed a value of 284 K upon the cold rolling (with the $R = 3$) of pure copper to 65 % under a non-lubricated condition. Recent results of a more detailed experimental study by Megantoro et al. [35] confirm that the temperature rise increases with increasing either the thickness reduction or the rolls speed ratio (showing a near-linear relationship). Consequently, these conditions allow activating dynamic structure restoration phenomena (namely, continuous or discontinuous dynamic recovery or recrystallization) leading to the formation of thermally stable (up to a certain temperature [36]) microstructure composed of dislocation-free volumes (grains, subgrains) with a size in the submicron range.

The second purpose for using the DSR processing—the control of a deformation texture that affects anisotropy of mechanical properties—is especially important in the case of aluminum and magnesium alloys. These materials mainly due to their very good strength to weight ratio are considered as candidates in many car and plane body applications. However, the main drawback of these materials is their lower formability (namely, a susceptibility to deep drawing) than conventional low carbon steels. Aluminum and aluminum alloys are well known for their high-mechanical property anisotropy (a so-called earing behavior) upon a deep drawing process. The presence of this kind of shape defects of processed components generates a necessity for using additional operations and a waste of large quantity of the material. It was recognized that the main determinant of such behavior is a {1 0 0}<1 0 0> cubic crystallographic texture formed in a fully annealed state. On the other hand, it was proposed by Lequeu and Jonas [37] that formation of the undesired {1 0 0}<1 0 0> recrystallization texture component may be prominently inhibited through an application of shear deformation prior a heat treatment. Therefore, a number of works have been devoted to a development of asymmetric rolling-based processing techniques that allow for the fabrication of aluminum alloy sheets with enhanced formability.

Engler et al. [38] reported that the most efficient method of the formability improvement is to introduce {1 1 1} textures (composed of crystallographic orientations that are characterized by {1 1 1} crystallographic planes parallel to a rolling plane). Since these orientations are normally found in bcc metals and alloys (and are responsible for an excellent drawability of low carbon steels), in the case of *fcc* metals, they may be produced only by shearing. Jin and Lloyd [39] proved that the recrystallization texture of AA5754 aluminum alloy is randomized (the {0 0 1}<1 0 0> component is prominently reduced), when a high-ratio (R = 1.5 and R = 2) asymmetric rolling is applied before the annealing treatment. The {1 1 1} shear deformation texture is maintained in the material after annealing that allows lowering a so-called planar anisotropy (that characterizes an alteration of mechanical properties in different directions lying in the rolling plane). Analogous results were also documented by Sakai et al. [40] who showed that 5052 aluminum alloy cold deformed to 75 % of thickness reduction in a two-pass asymmetric rolling process followed by recrystallization annealing at temperature of 310–460 °C exhibits almost perfectly isotropic mechanical behavior (values of the planar anisotropy coefficient were reduced to near zero). Similar findings on 5251 aluminum alloy were also presented by Polkowski and Jóźwik [41].

While magnesium alloys (especially these containing Al and Zn additions—a so-called AZ series) are in many fields superior to aluminum alloys (e.g., possess a lower density and thus a better specific strength), their problematic formability concerns even a greater attention. Over a last few years, a number of scientific works have been devoted to a fabrication of Mg alloy sheets with a good drawability. It was proposed that the main reason for a very poor cold formability and a high mechanical anisotropy is an induction of a strong {0 0 0 1} basal texture in conventional plastic-forming processing [42] due to limited number of slip systems in hexagonal close-packed (hcp) crystal structure [43]. Results of an extensive study on various Mg alloys, e.g., AZ31 [44–47], AZ91 [48], AM31 [49, 50], or ZK60 [51, 52] alloys, showed that the DSR has a great impact on the intensity of the basal texture and plasticity of these materials. Generally, it was established that increasing the shear deformation by raising either the rolls speed ratio or a rolling reduction leads to weakening of the basal texture through facilitating the activation of prismatic slip during deformation. The basal texture weakening effect at high speed ratios is attributed to extensive tension twinning that occurred in the basal-oriented matrix, which in turn is exceptionally found in a conventional rolling process. Consequently, the DSR-fabricated Mg alloy sheets are characterized not only by more isotropic properties but also by the enhanced plasticity combined with exceptionally high strength (that is related to the simultaneous structure refinement [53–55]). Therefore, the DSR process is considered to be one of the most efficient techniques for processing these materials.

A newly proposed interesting usage of the DSR process is a fabrication of composite materials via a powder compaction [56] or an improvement of properties of these materials in the additional step of a manufacturing process. It was recently reported by Yoo et al. [57] on the example of carbon nanotube/copper and by Kim et al. [58] in a study on TiC/aluminum metal matrix composites that the large amount of redundant shear strain induced during the DSR significantly facilitates the dispersion of the reinforcement (through breaking up their clusters), having also a positive impact on mechanical properties of processed materials. It is believed that this research direction will become more and more important in a near future.

By summarizing, it should be again underlined that the DSR process exhibits a great potential in a large-scale fabrication of bulk metal components with enhanced mechanical properties and formability. The high imposed shear strain leads to an extensive structural evolution involving a grain refinement, affecting a crystallographic texture and a distribution of "second-phase" particles. What is very important, resulting mechanical properties of DSRed materials are much better than those of conventionally cold-rolled materials and at least not worse than those of counterparts subjected to hydrostatic SPD methods while having an undeniable advantage of a better efficiency in terms of a larger quantity of processed material and a lower number of needed operations.

Author details

Wojciech Polkowski

Address all correspondence to: wpolkowski@wat.edu.pl

Department of Advanced Materials and Technologies, Faculty of Advanced Technologies and Chemistry, Military University of Technology, Warsaw, Poland

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