# Finite element analysis of the springback behavior after V bending process of sheet materials obtained by Differential Speed Rolling (DSR) method

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**ABSTRACT:** The Differential Speed Rolling (DSR) process is a severe plastic deformation method used in the production of microstructured materials with both high deformation and superior mechanical properties. This study has focused on determining the springback behavior and formability of the materials obtained by using the DSR method after the V bending process. Rolling processes were carried out at 4 different rolling speed ratios (1.0, 1.33, 1.66, and 2.0), 25% thickness reduction ratio, and 2 different rolling temperatures (room temperature and 580 °C). Then, the rolled sheet materials were bent using 3 different bending die angles (60°, 90°, 120°). As a result of this study, the greatest plastic deformation was reached at a speed ratio of 2.0 at 580 °C. Again, the lowest springback was obtained at 580 °C. As the die angle increased, the springback decreased. Springback has occurred in the bending process of all sheet materials obtained by rolling. In the bending process of the unrolled sheet material, both spring-forward and springback events were observed depending on the die angle.

KEYWORDS: Asymmetric rolling; Bending; Differential speed rolling; Severe plastic deformation; Springback

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**RESUMEN:** Análisis por elementos finitos del comportamiento de recuperación elástica después del proceso de flexión en V de materiales laminados obtenidos por el método de laminación de velocidad diferencial. El proceso de laminación de velocidad diferencial es un método de deformación plástica severa utilizado en la producción de materiales microestructurados que aplica una alta deformación y permite obtener buenas propiedades mecánicas. Este estudio se ha centrado en determinar el comportamiento de recuperación elástica y la formabilidad de los materiales obtenidos mediante el método de laminación de velocidad diferencial después del proceso de flexión en V. Los procesos de laminación se llevaron a cabo utilizando 4 relaciones de velocidad de laminación diferentes (1.0, 1.33, 1.66 y 2.0), una relación de reducción de espesor del 25% y 2 temperaturas de laminación diferentes (temperatura ambiente y 580 °C). Luego, los materiales laminados se doblaron usando 3 ángulos de matriz de doblado diferentes (60°, 90°, 120°). Como resultado de este estudio, la mayor deformación plástica se

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alcanzó a una relación de velocidad de 2.0 a 580 °C. De nuevo, la recuperación elástica más baja se obtuvo a 580 °C. A medida que aumentaba el ángulo de la matriz, disminuía la recuperación elástica. Se ha producido una recuperación elástica en el proceso de doblado de todos los materiales laminados obtenidos por laminación. En el proceso de doblado de la plancha de material sin laminar se observaron eventos tanto de avance como de recuperación dependiendo del ángulo de la matriz.

PALABRAS CLAVE: Laminación asimétrica; Flexión; Laminación de velocidad diferencial; Recuperación elástica; Deformación plástica severa

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## **1. INTRODUCTION**

Severe plastic deformation (SPD) can be defined as an ultra-fine-grained and nanostructured metal forming method because the materials undergo very large plastic deformation. With the SPD method, the particle size of the material can be reduced to the nano level (Głuchowski *et al.*, 2011; Solhjoei *et al.*, 2014; Nazari and Honarpisheh, 2018; Taşdemir, 2020b). Grain size is an important factor affecting almost all aspects of the chemical, physical and mechanical properties of polycrystalline metallic materials. One of the continuous severe plastic deformation methods used in the severe plastic deformation of sheet materials is the asymmetric rolling method (Loorent and Ko, 2014).

Asymmetric rolling (ASR) is a method that has been used since the 1940s as it reduces rolling force. Recently, its use has been increasing due to its potential to improve the microstructure and mechanical properties (Liu and Kawalla, 2012). ASR is an important technique used to control both the texture and grain size of metallic materials. ASR aims to create a large shear deformation homogeneously throughout the plate thickness by providing high friction between the sheet material and the rolls. The schematic view of the ASR method is given in Fig. 1. One of the most important advantages of ASR compared to conventional (symmetric) rolling is that the rolling force and the torque can be reduced. This allows a finer-grained structure to be obtained



**FIGURE 1.** Schematic representation of the asymmetric rolling process. (a) Different roll speeds; b) Different roll diameters.

due to the higher applied deformation (Fajfar *et al.*, 2017). In addition, ASR can provide extra shear deformation, which is effective not only in obtaining fine grain but also in modifying the crystallographic textures to achieve the desired properties (Li *et al.*, 2016).

Differential Speed Rolling (DSR) is an ASR process and is performed using two identical rollers but with different rotational speeds. This causes high shear deformation to be applied to the sample during the DSR process (Hamad and Ko, 2019). It is known that very small material thicknesses can be reached with high precision with the DSR process (Ji *et al.*, 2007). The DSR process also has different applications such as different roll speeds, different roll diameters, different friction coefficients, and different route types.

The equivalent strain after DSR processing is much larger than with conventional rolling. The equivalent strain obtained after the DSR process can be calculated theoretically with the formula given in Eq. (1), (Cui and Ohori, 2000).

$$\varepsilon_e = \left\{ 1 + \left[ \frac{(1-r)^2}{r(2-r)} \tan \theta \right]^2 \right\}^{1/2} \frac{2}{\sqrt{3}} ln \frac{1}{1-r} \qquad (1)$$

where,  $r = 1-(t_i/t_f)$ ,  $t_i$  and  $t_f$  are the material thickness before and after DRS treatment, respectively, and  $\theta$ is the shear angle.

Equation (2) can be used for rolling deformation.

$$\varepsilon_r = \frac{2}{\sqrt{3}} ln \frac{1}{1-r} \tag{2}$$

The shear strain ( $\varepsilon_s$ ) can be calculated by the following Eq. (3) (Kamikawa *et al.*, 2007).

$$\varepsilon_s = \frac{2}{\sqrt{3}} \frac{(1-r)^2}{r(2-r)} \tan\theta \ln \frac{1}{1-r}$$
(3)

For equivalent strain, a new equation can be written as given in Equation 4 by using Equation (1) - (3)together.

$$\varepsilon_{e} = \sqrt{\left(\frac{2}{\sqrt{3}} ln \frac{1}{1-r}\right)^{2} + \left(\frac{2}{\sqrt{3}} \frac{(1-r)^{2}}{r(2-r)} tan\theta ln \frac{1}{1-r}\right)^{2}}$$
(4)

Compared to SPD methods or even conventional rolling, the accurate determination of DSR strain before the DSR deformation may not be possible. To calculate the DSR strain, the apparent shear angle caused by the velocity asymmetry must be deter-

mined. This can only be measured after DSR deformation (Hamad and Ko, 2019). Indeed, in a study by Park *et al.* (2015), strain calculations during DSR deformation were made using a simple marking method.

Yu et al. (2013) conducted a study on the joining of AA1050 and AA6061 materials designed as sandwich panels with the ASR method. In their study, they stated that at the end of the third pass, the grain size decreased to 140 nm in AA6061 material and to 235 nm in AA1050 material. In addition, in their study with finite element analysis, they determined that the equivalent stress distribution in the samples obtained as a result of the asymmetric rolling is more uniform and higher than in the conventional rolling. Cui and Ohori (2000) stated in their study on the determination of the grain structure of pure aluminum using both conventional rolling and the ASR methods that the grain structure in the samples obtained as a result of the asymmetric rolling is both finer-grained and more homogeneous. Ucuncuoglu et al. (2014) conducted a study on the microstructure, mechanical properties, and material texture formed as a result of rolling AZ31 alloy using the ASR technique. As a result of their studies, they stated that the grain size, which was 10 microns as a result of symmetric (traditional) rolling, decreased to 0.7 microns as a result of the asymmetric rolling and that there were improvements in other properties. (Sidor et al., 2010) in their study on the effects of ASR treatment on plastic anisotropy and limit drawing ratio of 6016 aluminum alloy, they stated that ASR treatment improves these two properties and makes a positive contribution to formability. As it can be seen from these studies, the benefits of the ASR process are significant.

In this study, it was tried to determine the springback behavior and formability of the materials obtained by the DSR method after the V bending process. One of the most important deficiencies in this field is the investigation of the formability behavior of materials obtained by using severe plastic deformation methods. In this respect, this study is original. In addition, this study aims to contribute to this field.

## 2. MATERIALS AND METHODS

The finite element method is a widely used to better explain the deformation behaviors during forming, reduce production costs and determine the optimum parameters. "Simufact forming" program was used for this analysis. In the study, 100Cr6 material with the dimensions of  $2 \times 20 \times 50$  mm was preferred and all the data of the material were taken from the material library of the program. The material properties used in the analysis are given in Table 1 and the flow stress curves are given in Fig. 2. The

TABLE 1. Material properties used in FEM simulations

Material Properties	Value
Young's modulus, (GPa)	210 (25 °C), 164 (580 °C)
Poisson's ratio	0.3
Density, (kg/m <sup>3</sup> )	7850
Thermal expansions coeff., (1/°C)	1.21×10 <sup>-5</sup> (25 °C)
- · · ·	1.49×10 <sup>-5</sup> (580 °C)
Specific heat capacity (J/kg°C)	457 (25 °C), 712.2 (580 °C)
Thermal conductivity, (W/m°C)	33.7 (25 °C), 33 (580 °C)
Oyane damage model	
Damage threshold, C	0.4
Material constant, B	0.8



FIGURE 2. Flow stress curves for 100Cr6 steel.

workpiece is defined as 3D. The sheet meshing algorithm will automatically detect the thickness direction of the sheet and create an optimized mesh of 3D Solid Elements, also called hexahedral elements. The ability to use hexahedral elements is unique and provides the most accurate results possible. It is particularly good for predicting thickness variations, springback, and residual stresses. The hexahedral elements used are eight-node and isoparametric. During the simulation, the mesh is automatically re-meshed when required to enable tracking of the large deformations (Buijk, 2009; Harter et al., 2013). Work rolls are considered rigid. Figure 3 shows the system created for the analysis. The study was carried out using symmetric rolling (SR) (Fig. 4a), differential speed rolling (DSR) (Fig. 4b), and differential speed rolling with guide element (DSR-G) (Fig. 4c). Then, the rolled parts were subjected to the V bending process with all their features (stress, strain, material flow, etc.) (Fig. 5). The used boundary conditions allow the rolls to rotate only about their axis in rolling, while in V bending they allow the punch to move in the Z direction. In the rolling process, the friction law was selected as the automatic mode. This feature enables you to generate a friction object with an automatically selected friction law and its parameters in consideration of process-specific val4 • V. Taşdemir



**FIGURE 3**. The system created for the analysis of the Differential Speed Rolling Process Symmetric rolling if Vu=Vl, asymmetric rolling if Vu>Vl or Vu<Vl.

ues. In this mode, the simulation decides which friction law (Coulomb, Shear, Combined, IFUM) will be selected. When the process report was checked after the simulation, it was seen that the Coulomb friction law was used. The friction coefficient varies between 0.59 - 0.7 depending on the temperature change. Here, the scaling friction factor is not a concrete friction coefficient but a scaling factor for a qualitative description. For the V bending process, analyzes were made by selecting Coulomb friction law in manual mode. The rolling and bending pa-



FIGURE 4. Analysis images of a) SR, b) DSR and c) DSR-G processes.



FIGURE 5. Analysis image of V bending process.

	Differential speed ratio, (Vr=Vl/Vu)	1.0 (SR), 1.33 (DSR-1 and DSR-G), 1.66 (DSR-2), 2.0 (DSR-3)
	Reduction ratio (red), %	25
	Temperature, °C	25 (RT), 580
	Friction	Specification mode: Automatic
is		Scaling friction factor: 0.9
alys		Bad friction (µ): 0.59 - 0.7 (depending on temperature)
ans	Mesher	Sheetmesh
ng	Element type	Hexahedral
olli	Element size, mm	0.75
Я	Object type	Material: Elastoplastic
		Die: Rigid
		Punch: Rigid
	Upper and lower roll diameter, mm	40
	Sheet thickness, mm	2
<u>-</u>	Die and Punch angle, °	60, 90, 120
Ina	Punch radius, r (mm)	4
<u>s</u> . 2	Punch speed, mm/s	1
s	Sheet thickness, mm	Rolled sheet
ber	Friction	Specification mode: Manual
>		Friction law: Coulomb
		Friction coefficient (µ): 0.1

TABLE 2. Rolling and V bending parameters for finite element analysis

rameters used in the analysis are given in Table 2. Rolling processes were carried out both at room temperature and 580 °C. However, the V bending processes of all rolled samples were carried out only at room temperature. 60°, 90°, and 120° die angles are used in the V bending processes. The punch speed was kept constant at 1 mm/s. In addition, for the correct interpretation of the V bending results, the unrolled (UR) sheet was also bent. Sheet material thickness reduction ratio was determined as 25%.

## **3. RESULTS AND DISCUSSION**

A good analysis of the stress zones formed in the deformation zone provides some information about shear deformation and plastic zones (Nagasekhar *et al.*, 2007). In Fig. 6, the upper and lower rolling surfaces of the rolled samples by SR, DSR-1, and DSR-G methods are given. When the figures are examined, the stress values on both the upper and lower surfaces of the sample rolled with symmetric rolling are close to each other and are quite high.



**FIGURE 6.** Surface stress distributions of the samples analyzed by a) SR, b) DSR-1 and c) DSR-G methods (580 °C rolling condition).

The stress value on the upper surface of the sample rolled with the DSR-1 method is considerably higher than the stress values on the lower surface. In other words, the stress value at the lower surface is dramatically smaller than the stress value at the upper surface. In the DSR-G method, the stress values on both the upper and lower surfaces are closer to each other but not homogeneous.

In Fig. 7, the curvature radius of the samples obtained after rolling at different speeds is given. When the graph is examined, it will be seen that the curvature radius decreases as the speed ratio increases for both rolling temperatures. This is due to the increase in material flow rate due to the increase in the rolling speed. The radius of curvature also decreased when the rolling temperature increased from room temperature to 580 °C. The facilitation of forming with the effect of temperature and the reduction of post-forming stresses led to this situation. Similarly, Lee *et al.* (2014) stated that the increase in velocity ratio decreases the radius of curvature.



**FIGURE 7.** Curvature radius values in samples obtained as a result of differential speed ratios.

Plastic deformation has a significant effect on both hardness distribution and internal microstructure homogeneity (Faraji *et al.*, 2012). In this respect, plastic deformation is an important indicator. Figure 8 shows the average effective plastic strain



**FIGURE 8.** The average effective plastic strain of the upper and lower surfaces of the samples obtained as a result of differential speed ratios.

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**FIGURE 9.** Effective plastic strain on the upper and lower surfaces after DSR-3 processing (580 °C rolling condition).

values on the upper and lower surfaces of the samples rolled with different rolling methods. In Fig. 9, the plastic deformation of the upper and lower surfaces of the sample rolled with the DSR-3 method is given. When Fig. 8 is examined, it is seen that the plastic strain values on the upper surfaces are almost close to each other, but the plastic strain values on the lower surfaces are different from each other. This is because the material flow on the lower surface is much higher due to the speed increase in the lower roll. It is also clearly seen that there is no change in the plastic deformation on both the lower and upper surfaces in the SR process. In addition, in the DSR-1, DSR-2, and DSR-3 processes, it is seen that the plastic strain values after rolling at 580 °C are higher than the plastic strain values at room temperature. This shows that plastic deformation increases with the effect of temperature.



**Figure 10.** End shapes of rolled sheets: a) SR, b) DSR-G, c) DSR-1 d) DSR-2, c) DSR-3.

The end forms of the rolled samples are given in Fig. 10. It is seen that the end form deteriorates as the speed ratio increases.

Springback is one of the main defects in metal forming and is caused by the elastic nature of the material. Springback is measured as the difference between the design of the parts and the shape after they are formed. Springback / spring-forward, which occurs as a result of removing the load from the material in the shaping process, affects the geometric integrity of the products, production cost, production time, etc. adversely affects it and even causes serious shape errors (Bakhshi-Jooybari et al., 2009; Darmawan et al., 2018; Taşdemir, 2020a). During bending, compression occurs on the inner surface of the bent region and tensile occurs on the outer surface. These tensile and compressive stresses play an important role in springback (Firat et al., 2008; Şen and Taşdemir, 2021). The amount of springback in the bending process depends on many factors such as the mechanical properties of the material, bending radius, die clearance, material thickness, bending angle, forming temperature, and holding time of the punch (Gürün et al., 2018; Şen and Taşdemir, 2021).

Figure 11 shows the springback values of the samples obtained by using different rolling methods after 90° bending. While springback occurred in the SR, DSR-1, and DSR-G processes, spring-forward occurred in the unrolled (UR) sample. The highest springback occurred in the DSR-G process at room temperature. The non-homogeneous stresses formed in the sample flattened with the guide placed at the rolling exit after shaping increased the amount of springback.

Three different bending zones were determined after the bending process in the samples which were bent after all DSR processes. The first is in the region close to the bending radius, the second is in the middle of the bent part, and the third is in the region near the end of the part. This situation is illustrated in Fig. 12. Due to the curvature after DSR processes, support is formed at the tangential point of the sample placed in the die that contacts the die, which increases the stresses in the bent part.



**Figure 11.** Effect of various rolling methods on springback after V bending (90° die angle results).

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**Figure 12.** V bending process and bending regions of samples obtained by DSR method: a) before bending process, b) and c) during bending process (V bending after DSR-1 process).

The effect of differential velocity ratios on springback is given in Fig. 13. When the graph was examined, it was observed that the lowest springback occurred in the rolled samples at both room temperature and 580 °C. Considering the effective plastic strain in the material, it can be said that the springback after DSR processes is lower than the SR (1.00) process. Figure 14 shows the effect of die angle on springback. When the figure is examined, it can be said that as the die angle increases, the springback decreases. Inversely proportional to the increase in the die angle, the deformation in the bending region decreases. This results in lower stress formation in the bending region. The number of springback increases or decreases in proportion to the stress formed in the bending region. In other words, as the die angle increases, the bending moment in the bending region decreases, which reduces the springback angle, (Trzepiecinski and Lemu, 2017; Aydin and Karaağaç, 2019; Ma *et al.*, 2019). In the unrolled (UR) sample, springback occurred in bending with 60° die, while spring-forward was observed in bending made with 90° and 120° die. This is thought to be due to the structure of the material. On the other hand, in the sample subjected to the DSR-3 (2.00) process, springback occurred at all bending angles. In the SR (1.00) treated sample, a slight increase was observed in the springback when the bending angle increased from 60° to 90°, but a significant decrease occurred at 120°. This situation



Figure 13. Effect of speed ratio on springback (90° bend angle).

Figure 14. Effect of die angle on springback (RT results).

revealed how important the deformations applied to the material are in shaping.

## 4. CONCLUSIONS

In this study, V bending processes of materials rolled by differential speed rolling method, which is one of the methods in severe plastic deformation, were analyzed using the finite element method. As a result of the study, the following results were obtained.

- As the velocity ratio increased, the plastic deformation increased.
- The plastic deformation obtained as a result of the DSR process at 580 °C is greater than at RT.
- The radius of curvature decreased as the speed ratio increased.
- In the samples rolled by the DSR method, 3 different bending zones were formed as a result of V bending.
- The unrolled (UR) material showed spring-forward at small die angles and springback at large die angles.
- In general, the springback in samples obtained by DSR methods is lower when compared to symmetrical rolling. However, the greatest springback (7.775°) event was observed in the DSR-G method.
- As the die angle increased, the springback decreased. In other words, as the bending angle increased, the springback increased. It can be said that the reason for this situation is that the increase in the bending angle increases the bending moment in the bending region.
- This study is also expandable with many different parameters (such as thickness reduction ratio, different rolling diameters, different friction coefficients, mesh parameters, different material types, multi-materials, different bending methods such as air, L, U, offset).

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