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A REVIEW OF ASYMMETRIC ROLLING

OSNOVNI PREGLED ASIMETRIČNEGA VALJANJA

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The metal-forming industry is increasing its array of products every year. A connection between scientific research and practical examples from industry keeps improving the rolling processes. A historical overview proves that asymmetric rolling has been an interesting topic of many studies for more than six decades. Once performed only on steels and aluminium alloys, this process has outgrown the basic types and its application was extended to other metal alloys. This paper presents a basic review of asymmetric rolling focusing on activities in the roll gap and special mechanisms in deformation zone. Moreover, the effect of asymmetric rolling on the rolling force, torque, reduction and deformation was explained and supported with different results from scientific research. The microstructure and texture differences in comparison to the conventional (symmetric) rolling were discussed as an improvement of the mechanical properties. Besides the comparative study between simulations and experimental rolling, regarding the undesirable ski-effect, the discussion in this paper is always reinstating the possibilities of using asymmetric rolling in industry.

Keywords: rolling, types, deformation zone, ski-effect, characterization

Obseg valjanih proizvodov se v metalurško-predelovalni industriji iz leta v leto povečuje. Ob povezovanju znanstvenih raziskav z dobrimi primeri iz industrije se tudi valjarni procesi in postopki vedno znova izboljšujejo. Zgodovinski pregled dokazuje, da je asimetrično valjanje zanimiva tematika številnih raziskav že več kot šest desetletij. Nekaj osnovnih postopkov asimetričnega valjanja je v tem času preraslo v posebne načine asimetričnega valjanja, ki so se najprej izvajali na jeklih in aluminijevih zlitinah, nato pa prehajali na številne druge kovinske zlitine. Pregledni članek predstavlja osnovni pregled asimetričnega valjanja, kjer je podrobno razloženo dogajanje v valjčni reži in so predstavljene posebnosti mehanizmov v deformacijskem območju. Nadalje so razlage vplivov na silo in moment valjanja, na redukcijo ter deformacijo podkrepljene z različnimi rezultati opravljenih raziskav. Mikrostrukturna in teksturna razlikovanja v primerjavi s klasičnim (simetričnim) valjanjem so obravnavana kot vzrok za izboljšanje mehanskih lastnosti. Ob primerjalni študiji simulacij in realnega valjanja za neželen upogib obdelovanca se razprava pri članku vedno znova vrača na možnosti uporabe asimetričnega valjanja v industrijskih obratih.

Ključne besede: valjanje, načini, deformacijsko območje, upogib valjanca, karakterizacija

1 INTRODUCTION

The importance of activities in the metal forming industry is nowadays not only due to economic reasons, but rather due to environmental and social impacts. The automotive industry represents the main branch of forming industry[1] and is forced to accommodate an increasing environmental aspect, to a greater extent. Just a few special deformation techniques for the improvement of mechanical properties with the creation of ultrafine grained microstructure are known.[2] The equal channel angular pressing (ECAP)[3] and high pressure torsion (HPT),[4] which are more laboratory limited processes, and on the other hand, asymmetric rolling, which can be suitable for use in industrial plants.[2] The same as conventional or symmetric rolling, asymmetric rolling was successfully investigated at elevated[5], as well as at low[6] temperatures.[7] Besides many different metals and their alloys, the desirable, positive effects of asymmetric rolling were developed on products with different shapes.[8] Not only on thick[9] and thin[10] sheets, it was also performed on strips,[11] wires,[12] billets[13] and foils.[14]

2 HISTORY

The theory of asymmetric rolling was already known and well explained in 1941.[15] More than ten years later, in 1957, the first laboratory or industrial experiments were performed and technological results were published.[16] With new ideas and developments in 1966, the researches of single-drive rolling[17] and rolling with different roller diameters were the most intensive.[18] Later, in 1972, there was more emphasis on different impacts on the ski effect, as a unique phenomenon.[19] One of the first models and the finite-element approach for asymmetric rolling occurred in 1994. In the same year, the ideas of introducing asymmetric rolling into industry appeared.[20] In 1997 a very important distribution of asymmetric rolling types and cases was made.[21] With each year, through decades, asymmetric rolling was becoming more and more developed, but new challenges and studies of asymmetric rolling remain.

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3 CATEGORIES OF ASYMMETRIC ROLLING

The distribution of asymmetric rolling in most cases covers four major rolling types. These four as well as some other special types, are influenced by the velocity, geometry and friction.[22] In every asymmetric rolling type one parameter has the highest influence, nevertheless that each type has an impact on all three mentioned parameters.[21,23,24]

3.1 Different rotation speeds of the rollers

Probably the most appropriate asymmetric rolling type for industry is rolling with different rotation speeds of the rollers.[23] The rollers' dimensions are in that case the same. The greatest impact on the deformation zone is the speed difference on the workpiece velocity. The discussed asymmetric rolling type (**Figure 1**) can be performed with a faster driven upper roller,[25] or a faster driven lower roller,[26] which has a different impact on the friction. Higher friction in the deformation zone has appeared in the area of the faster roller. All the described effects already arise at very small speed differences, but more significant asymmetric effect contributions are created with 5 m·s^{-1} rotation speed difference.[27,28] The factor of asymmetry f_a for asymmetric rolling with different rotation speeds of the rollers v was calculated with the Equation (1):

$$f_a = \frac{v_{faster}}{v_{slower}} \quad (1)$$

3.2 Different diameters of the rollers

The rolling process where asymmetry is provided with different dimensions of the upper and lower work rollers, presented in **Figure 2**, has great impact on the geometry and results in a strong curvature of the workpiece. More significant bending is visible at diameter differences of 10 mm, where the lower geometrical irregularities of the workpiece have already appeared in the case of a lower dimensional difference.[29,30] The speed of rollers was, for this type of asymmetric rolling, the same for the upper and lower rollers. A smaller roller, where the friction is higher, can be installed on the upper[31] or on the lower[32] position of the rolling mill.[33,34]

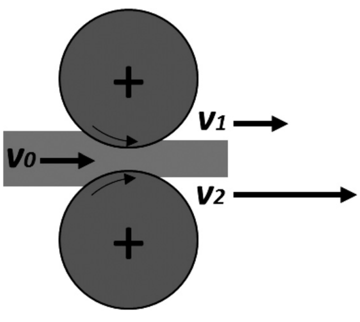

Figure 1: Asymmetric rolling with different rotation speeds of the rollers

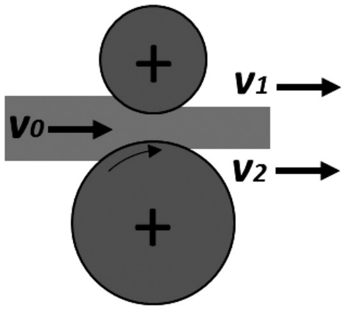

Figure 2: Asymmetric rolling with different diameters of the rollers

The factor of asymmetry f_a was for asymmetric rolling with different diameters of rollers D, calculated with Equation (2):

$$f_a = \frac{D_{larger}}{D_{smaller}} \quad (2)$$

3.3 Single-drive roller

Similar to the asymmetric rolling with different rotation speeds, but with greater friction differences in deformation zone, single-drive rolling can be performed (**Figure 3**). This type of asymmetric rolling has a higher impact on the friction and workpiece velocity. In this case of rolling type the rollers' diameters are the same. Higher friction appeared in the contact between the workpiece and the driven roller. In most cases, the upper work roller is idle, but it also works the other way around.[35] A common issue with this kind of asymmetric rolling is gripping of the workpiece.[36] The presented asymmetric rolling type is possible to perform with a big enough grabbing angle and friction on entry of the deformation zone.[37] To calculate the factor of asymmetry f_a for single drive roller with the set speed 0 m·s^{-1} of one roller cannot be taken into account. With the as performed rolling set up, the mentioned factor will always be 0 or 1, which is incorrect. For the calculation of the factor of asymmetry, the speed v of the idle roller is used, as presented in the equation:

$$f_a = \frac{v_{driven}}{v_{idle}} \quad (3)$$

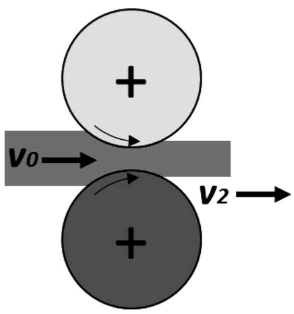

Figure 3: Asymmetric rolling with a single drive roller

3.4 Differently lubricated roller surfaces

During the rolling process, lubrication has the greatest impact on the friction (**Figure 4**). The roller diameters and rolling speeds are the same with differently lubricated roller surfaces asymmetric rolling type.[38] The reduction in friction will appear in the case of using different lubricants, as well as in the case of partial lubrication.[39] A drawback of different lubricants usage is the possibility of surface contamination.[27,40] The factor of asymmetry f_a can be, for different lubricated rollers surfaces, calculated as the difference between the friction coefficients μ:

$$f_a = \frac{\mu_{\text{higher}}}{\mu_{\text{lower}}} \quad (4)$$

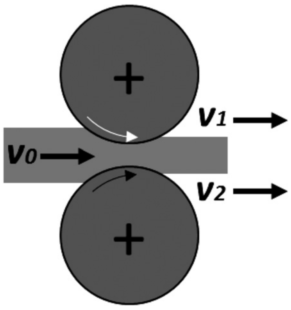

Figure 4: Asymmetric rolling with different lubricated roller surfaces

3.5 Special asymmetric rolling types

The special asymmetric rolling types also include combinations of four basic types, described above. More cases of rolling with different diameters and different speeds of rollers are known, as well as the reduction of friction for a single-drive roller with differently lubricated roller surfaces. Further, the asymmetric rolling type with displaced axis was performed.[41,42] Also, the dead block as the interface between the roller and the workpiece was used.[1,43] Thermal experiments with asymmetric cryo-rolling were also conducted.[44] Besides new ways of electro plastic deformations,[45] the mechanical specifics were studied also on multirole asymmetric rolling.[46,47] Some experiments were also conducted as a combination of single-drive rolling and equal-channel angular pressing, the two process for material production with a fine-grained microstructure.[48]

4 ROLL GAP AND MECHANICS IN THE DEFORMATION ZONE

Due to the introduced asymmetry in the rolling process the reduction of material from the upper and lower rollers are not the same. A higher reduction from the lower roller will be created, when the mentioned roller is driven faster than the upper roller.[49] On the other hand, if the speed of the upper roller is higher, a greater reduction appears in the area of the upper roller. The speed differences between the work rollers are the result of a different workpiece velocity during the plastic deformation zone. On entry to the deformation zone, the workpiece has a lower velocity than both rollers. After passing that zone, the workpiece has a higher velocity than the slower roller, but a lower velocity than the faster roller. Upon exit, the velocity of the workpiece is higher than both the driven work rollers. Among all the presented velocity rates, the workpiece is in contact with both rollers.[50] The contact length L for asymmetric rolling with different rotation speeds of rollers, presented in **Figure 5**, was calculated with the Equation (5):

$$L = \sqrt{R \cdot (h_1 - h_2) - \left(\frac{(h_1 - h_2)}{2} \right)^2} \quad (5)$$

where R is the radius of the rollers, h_1 and h_2 present the entry and exit thicknesses of the workpiece.[23] In combination with the results of the presented equation, the approximation of the important parameter Δ for the end dimension of workpiece is shown in the Equation (6):

$$\Delta = \frac{h}{L} \approx \frac{h_2}{\sqrt{R \cdot (h_1 - h_2)}} \quad (6)$$

where all the symbols for the parameters are the same as in the previous equation.[51] With variations of different rolling parameters, we can influence the geometric, kinetic and mostly friction properties of the workpiece in the deformation zone. According to the presented unequal velocity of the workpiece and rollers, the resulting rolling forces F, stresses σ and strains ε have worked differently. In the case of the asymmetric rolling, the tensile and compressive forces, and consequently the stresses and strains, that are also present at the symmetric rolling, produce more of the shear components of quantities mentioned above. The factor of asymmetry has a major impact on the creation of a higher share of the shear quantities with all the known asymmetric rolling types.[40,49] The difference between the forces and their associated stresses and strains for the symmetric and asymmetric rolling are presented with the matrix in **Figure 6**. The states of the shear-orientated stresses τ

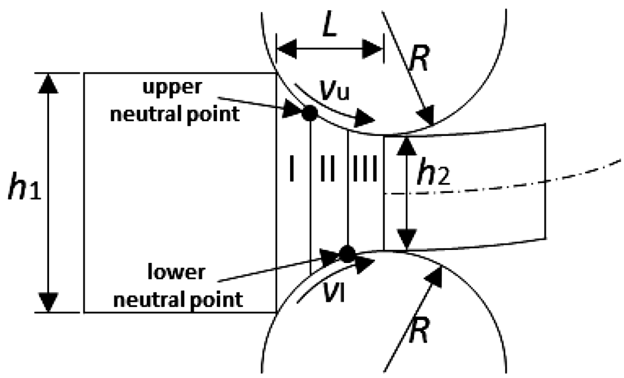

Figure 5: Deformation zone of asymmetric rolling with different rotation speed of rollers

and strains γ in the matrix depend on the asymmetric rolling type and the rolling direction.[52,53]

$$\begin{bmatrix} F(\sigma,\varepsilon) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -F(\sigma,\varepsilon) \end{bmatrix} \begin{bmatrix} F(\sigma,\varepsilon) & 0 & \pm F(\tau,\gamma) \\ 0 & 0 & 0 \\ \pm F(\tau,\gamma) & 0 & -F(\sigma,\varepsilon) \end{bmatrix}$$

$(a) \qquad (b)$

Figure 6: Matrix of force, stress and strain condition for: a) symmetric rolling, (b) asymmetric rolling[52,53]

Because of the unchanged energy balance during the rolling process, regarding the kinetics and friction differences, the vertical position of the neutral points in the deformation zone has changed. The neutral points, compared to the symmetric rolling, have changed their vertical positions depending on the asymmetric rolling type and their kinetics, geometrics or friction differences. The relationship between the position of the upper neutral point N_u and the lower neutral point N_l for asymmetric rolling with different rotation speeds of the rollers are given by the Equation (7):

$$N_u = \sqrt{\frac{\omega_2}{\omega_1} \cdot N_l^2 + \left(\frac{\omega_2}{\omega_1} - 1\right) \cdot \frac{h_2}{R}} \qquad (7)$$

where ω_2 and ω_1 are the peripheral speeds of the faster and slower roller, R is the radius of the rollers and h_2 is the exit thickness of workpiece. A delay of the neutral points has created three zones in the plastic deformation zone, which are also in conjunction with the speed relationship between the workpiece and rollers, as well as with the area of the shear orientated forces. In zone I on entry and zone III on exit the forces with their belonging stresses and strains are normal. Zone II, in the middle, where the velocity of the workpiece is faster than one roller and slower than the other roller, the area of more shear directed forces, stresses and strains was created.[49,51] The distribution of the plastic deformation zone on three zones is suitable for asymmetric rolling with different rotation speeds of the rollers,[49,50] as well as for asymmetric rolling with different diameters of the rollers.[29,54,55]

In a special case of asymmetric rolling with different geometric dimensions of the work rollers or with the roller's axis displacement, the deformation zone can be divided into four zones (**Figure 7**). For that kind of distribution, the bonding point x_b must be introduced. Zone I is in that case from the entry to bonding point x_b. From there to the neutral point of the smaller roller x_{n1} is zone II. The continued zone III has taken an area between a neutral point of a smaller roller x_{n1} and a neutral point of a bigger roller x_{n2}. Last but not least, zone IV is a continuation of the previous zone to the exit of the deformation zone. The length of the deformation zone L for the asymmetric rolling with different diameters of rollers can be calculated with the Equation (8):

$$L = \sqrt{R_{eq} \cdot h_i \cdot r} \qquad (8)$$

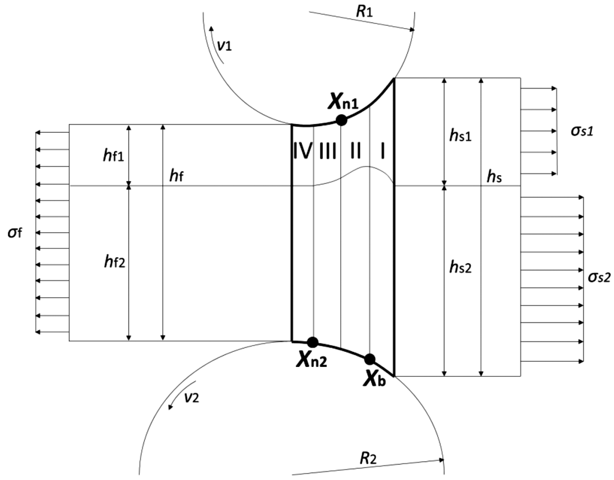

Figure 7: Special distributed deformation zone of asymmetric rolling with different diameters of the rollers

where the equivalent work roller radius R_{eq} can be determined by the Equation (9):

$$R_{eq} = \frac{2R_1 \cdot R_2}{(R_1 + R_2)} \qquad (9)$$

furthermore, h_i is a present entry thickness of a workpiece and r is the reduction of the material. R_1, in second equation, presents the radius of the smaller roller and R_2 is the radius of the bigger roller.[41,56]

5 TECHNICAL PARAMETERS

Variations of kinetics, geometrics and friction parameters change the longitudinal speed of the workpiece in the deformation zone. Consequential processes in the area of the upper and lower work roller have an impact on the critical angle and the forward or backward slip, which improves the productivity of the rolling operation in the reduction of the rolling force, pressure and torque, increases the reduction of material and improves the surface properties of the workpiece. Unfortunately, for the same reasons we have the unwanted bent part of workpiece, known as the ski effect.[49,57]

5.1 Rolling force and torque

The asymmetric rolling is based mainly on a direct action being applied on the workpiece in the deformation zone, where the occurring longitudinal tensile stresses, owing to the asymmetry in the forming process, have the effect of reducing the magnitude of unit pressure in the roll gap. Furthermore, the equalization of the non-uniform distribution of the rolled workpiece was created as a consequence of the mentioned effect. The regulated distribution over the workpiece shape in thickness, length, flatness and the cross-section results in the reduction of the total rolling force.[58] The rolling force applied across the constant contact length and the workpiece width present the normal contact stress. This can be divided into the deformation resistance of the material and the longitudinal supporting stress. The reduction of the longitudinal supporting stresses is, as mentioned, possible with the creation of longitudinal tensile stresses with types of asymmetric rolling and is more compatible as a reduction of the deformation resistance, which depends on the strain, strain rate and specific temperature.[59] In simple terms, torque is a product of force and distance, which are in rolling process the contact length. The rolling force and torque are reduced during the asymmetric rolling, but each type has its own particular manner which also depends on the efficiency of the rolling force and the torque reduction. The impact of the diameter difference will be apparent in the lower pressures and the smaller contact distance. With larger geometric differences, both mentioned quantities decrease more. According to the presented changes in **Figure 8a**, a decrease of the rolling force and rolling torque, which need to be summed as the torque of upper and lower rollers, is presented. On the other hand, due to impact of the speed difference, the contact distance stays more-or-less unchanged. Nevertheless, pressure decreases with a higher speed difference, similar to the diameter difference. The rolling force decreases according to the decreased pressure, and the torque of the slower roller consequently increases (**Figure 8b**). The rolling torque of the faster roller can be negative and the same as with the diameter difference summed to the torque of the other roller.[40,60] Compared to symmetric hot rolling, the rolling force during asymmetric hot rolling of austenitic steel decreased with increasing rolling temperature and descending reduction. The trends of rolling force decrease with the increasing diameter differences also occurred. Comparing the symmetric hot rolling with the asymmetric hot rolling of AA 5182 aluminium alloy, the rolling forces were reduced by 5 % to 30 %.[61–63]

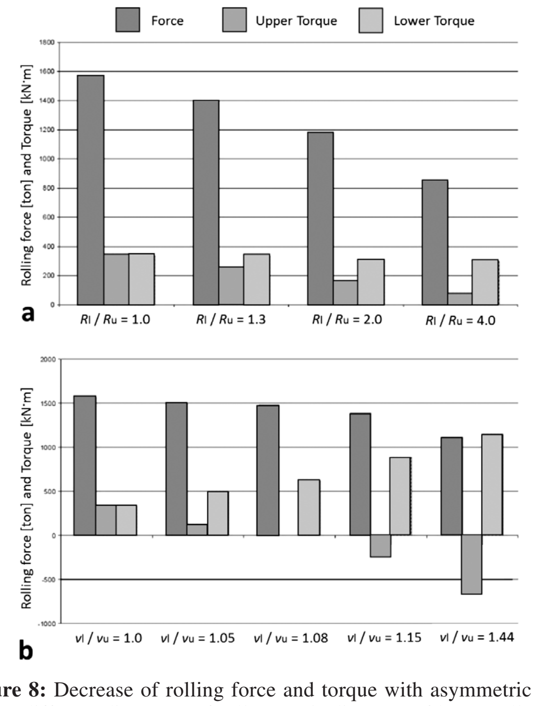

Figure 8: Decrease of rolling force and torque with asymmetric rolling: a) different diameters of rollers (R_l is diameter of lower roller and R_u is diameter of upper roller), b) different rotation speed of rollers (v_l is rotation speed of lower roller and v_u is rotation speed of upper roller)[40]

5.2 Reduction and deformation

The decreased magnitude of the rolling force has at the same time a direct impact on the elastic deflection of the whole rolling mill and an indirect effect on the roll gap shape that determines the exit dimensions of the workpiece.[58] In conjunction with the smaller elastic deflection, also the jump of the rollers was less significant. Overall, the exit thickness of the workpiece will be closer to the set height of the roll gap. Moreover, the higher reductions and strains for each rolling pass were achieved. Besides that, a decrease of the pressure and better distribution of them throughout the workpiece with asymmetric rolling enables the metal forming process, where higher strains with a lower rolling force were created. The economic advantages in industry are also in more rolling passes. In this case, reversed rolling can be considered. Due to higher strains having been reached, fewer passes in the rolling schedule are needed to achieve the desired exit dimensions. Consequently, the operating costs as well as the wear of the rollers decreased.[42,64,65]

5.3 Ski effect

Rolling with asymmetric conditions causes bending of the rolled workpiece towards the direction of one roller. This technical phenomenon is referred to as the ski effect. Generally, it is declared as an undesired bending effect, because further material transport on proceeding process can be obstructed and might damage the rolling mill's components.[66] Different rolling parameters have bigger or smaller impacts on the creation of the ski effect. Besides all the introduced asymmetries, also the temperature as well as entry and exit thickness of workpiece influences the creation of the ski effect.[57,66] If different interface frictions are applied, the curvature of the workpiece, or the ski effect, always goes towards the roller with the greater friction. The increased magnitude of the ski effect is shown with increased draft and friction difference.[67] With asymmetric rolling, where the speed difference of rollers is applied, the bending is more significant, the thicker the workpiece.[68] To reduce or to eliminate ski effect, the angle of the workpiece at the entry to the deformation zone needs to be changed. The inclined entry can be done with a rolling table adjustment. The curvature can be also simulated or calculated on different modes.[40,69] Each calculation or prediction has some special features and other influencing factors.[70,71] Therefore, the simulations' approximations can be very precise or totally mistaken. The type of

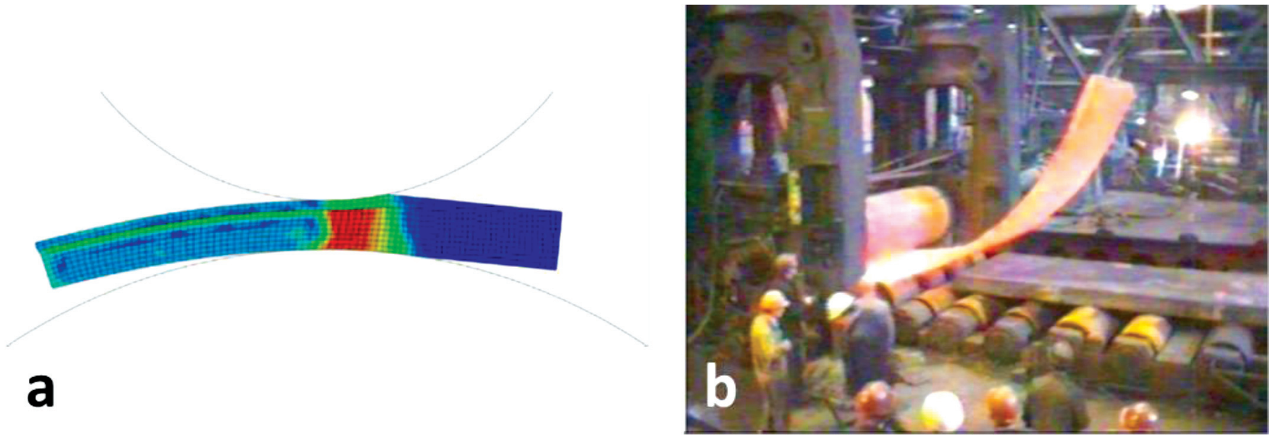

Figure 9: Ski effect: a) simulation, b) real example in the steel industry (not with the same rolling parameters)[24,56]

asymmetry has a strong impact on the accuracy and relevance of the predictions and calculations.[72] Simplification of the specifics of the ski effect can be explained with two effects that contribute to the bending of the workpiece. The first is due to the difference in the axial strains at the rollers' surface and the second is due to the difference in the shear strains at the same inter-surface area.[50] The calculated and simulated ski effect for laboratory rolling is presented in **Figure 9a.**[56] **Figure 9b** presents the real ski effect of a steel workpiece in industry.[24]

6 MATERIALS

Among extensive investigations of asymmetric rolling performed on many different metal alloys and compounds, asymmetric rolling was also performed on low-carbon steels,[73] silicon steels,[74] duplex stainless steels,[75] austenitic steels,[61] high-strength low-alloy steels (HSLA)[32] and some others.[76,77] Asymmetric rolling is for further investigations, besides work hardening aluminium alloys from series AA 5xxx[11,36,78] and AA 3xxx,[79] also interesting for some other aluminium alloys. For example, for the alloys from series AA 6xxx, where the heat treatment process is important.[80,81] A lot of research was done on pure aluminium.[82] The most often used for asymmetric rolling is also the magnesium alloy AZ31.[83,84] Besides the mentioned alloys, the effects of asymmetric rolling were also studied on high-entropy alloys (HEA),[85] tantalum,[86] copper,[87] different titanium sheets,[88] as well as on zinc alloy sheet.[89]

7 MICROSTRUCTURES

To analyse the improvement of the mechanical properties, a comparison between symmetric and asymmetric rolling needs to be made.[80,90,91] In **Figure 10** the microstructure of the same material with symmetric and asymmetric rolling is shown.[92] The microstructure of the symmetrically rolled material consists of more-or-less elongated grains, fragmented into equiaxed sub-grains. With applied asymmetry, significant changes in the microstructure were observed. A characteristic band structure appeared.[80,90,91] Compared to symmetric rolling, the asymmetric rolling leads to a refinement of the microstructure with very elongated bands fragmented into sub-grains (**Figure 11a**). Just like the average crys-

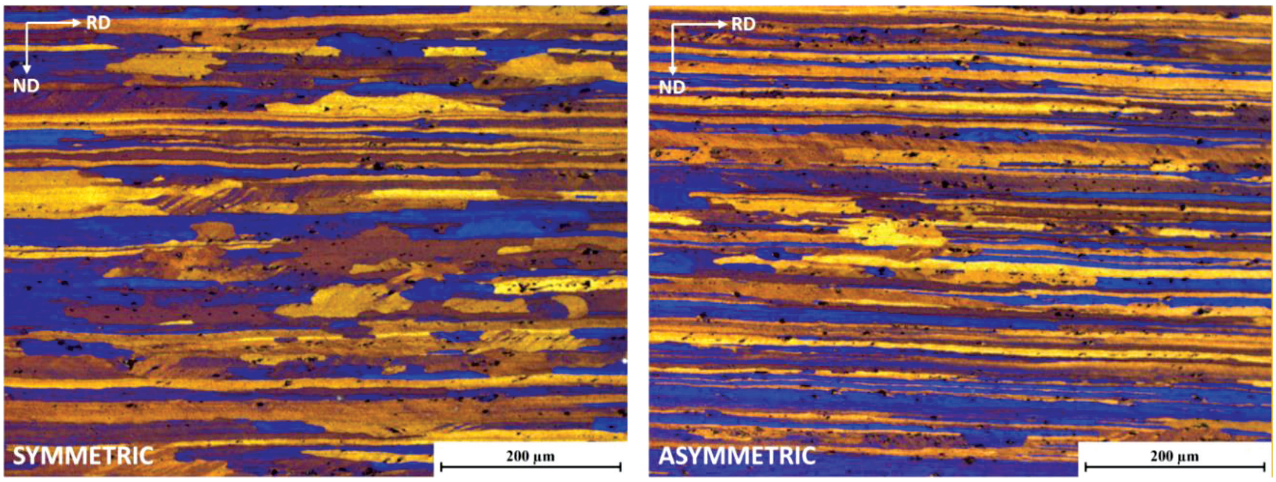

Figure 10: Microstructure of symmetric and asymmetric rolled aluminium

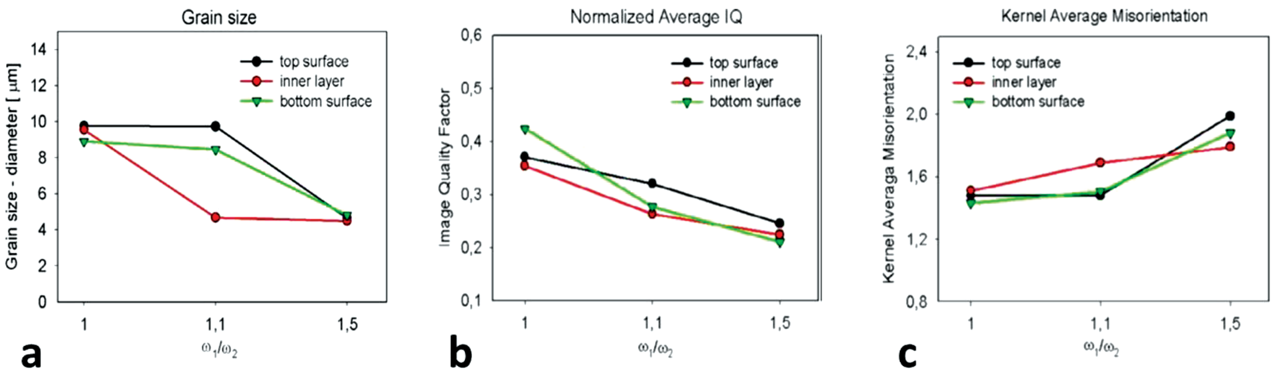

Figure 11: Microstructure changes: a) average grain size, b) image quality, c) kernel average misorientation[90]

Table 1: Grain refinement of different materials with asymmetric rolling[5,40,80,90,91,93,94]

Material	Temperature of metal forming process	Strain (%)	Average grain size SYMMETRIC rolling (µm)	Average grain size ASYMMETRIC rolling (µm)	Type of asymmetric rolling (factor of asymmetry)
Aluminium Alloy **6061**	COLD	36	9.0	4.0	Speed difference (1.5)
Aluminium Alloy **6111**	COLD	50	25.0	20.0	Diameter difference (1.5)
Aluminium Alloy **6016**	HOT	20	90.0	32.0	Diameter difference (1.5)
AR-CMnNb steel	HOT	50	7.1	5.8	Diameter difference (1.5)
C-Mn steel	HOT	35	14.7	13.6	Idle roller (/)
Low C steel (0.07 *w*/% C)	COLD	50	82.5	78.8	Speed difference (1.3)
Pure **Mg**	COLD	50	2.3	2.1	Diameter difference (1.5)

tal grains size is reduced, the image quality factor is smaller with an increased factor of asymmetry (**Figure 11b**). In contrast, the disorientation was increased with a higher factor of asymmetry (**Figure 11c**).[90] The ratio of the grain refinement depends on the material itself, the temperature of the metal-forming process, the achieved strain, as well as the asymmetric rolling type and the factor of asymmetry. **Table 1** presents all the mentioned impacts for seven different cases. For all the compared microstructures, the major purpose of smaller or greater grain refinement was reached with asymmetric rolling.[5,40,80,90,91,93,94] With the asymmetric rolling, also higher homogeneity of grain size distribution throughout the cross-section appeared.[95] When the relations between the symmetric and asymmetric rolled average grain sizes are defined, the comparison of the microstructure changes between the different asymmetric rolling types and the different factors of asymmetry is open for further investigations.[77,96–98] Besides, the heat-treatment before and after the deformation process is investigated as key impact for the microstructure changes.[13,78]

8 TEXTURES

Crystallographic texture engineering is a powerful and effective tool for obtaining differences in the deformation and recrystallization mechanisms. Just like other microstructure characteristics, the texture has several impacts on the mechanical properties.[99] With asymmetric rolling the heterogeneity of texture is a desired phenomenon.[100,101] To understand the differences and effects of them, the major created texture components and fibres with conventional deformation processes, for most of steels with body-centred cubic (bcc), aluminium alloys and some other non-ferrous metals with face-centred cubic (fcc) and magnesium alloys with hexagonal close-packed (hcp), need to be known.[99–101]

Hot and cold rolling of steel (bcc) has produced textures with increased α-fibre n||RD ({001}<110> to {111})<110> and γ-fibre {111}||ND ({111}<110> to {111}<112>). After recrystallization, a decrease of α-fibre appeared, so that only γ-fibre {111}||ND remain. Asymmetry in the rolling process displaces the γ-fibre {111}||ND with shear components in the orientation space. This displacement is in the opposite direction to the one where the shear components are reversed.[9,102]

In the case of aluminium and aluminium alloys (fcc) different textures with different texture components are created with hot and cold rolling. With hot rolling the most prominent fcc recrystallization texture components appeared. The cube component {001}<100> has characteristic shifts or scatterings of the orientation peak. During cold rolling, a typical fcc rolling texture develops. With low strains the connection between the G (Goss) {110}<001> texture component and B (brass) {011}<211> as α-fibre is created. More frequently, with greater strains the connection between C (copper) {112}<111>, S {123}<634> and B (brass) {011}<211> as β-fibre is created (**Figure 12**). The major idea and purpose of asymmetric rolling is the creation of shear

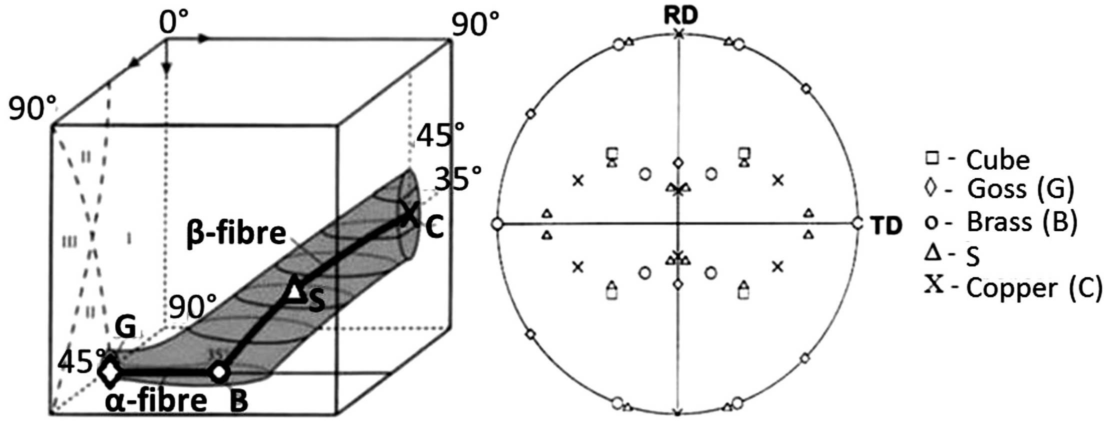

Figure 12: Major texture components and connected fibres presented in Euler space and with a pole figure

texture components. Most of them are with a {111}||ND orientation.[8,99,103–106]

In contrast to aluminium and steel, which can be cold deformed to the desired scales, the reductions to the final dimensions of magnesium alloys (hcp) have to be performed at elevated temperatures between 300 °C and 450 °C. At ambient temperature, the plastic deformation of magnesium is limited to two main deformation mechanisms, {0001} basal slip and {10-12} mechanical twinning. Other slip systems, such as {10-11} prismatic slip and {10-11} pyramidal slip, have the same <α>-slip direction in common, but they require a larger critical resolved shear stress for activation.[99] AZ31 is a typical magnesium alloy sheet in most investigated cases. It exhibits strong basal-type textures with grain orientations having basal planes parallel to the sheet plane. The stronger intensity of the basal texture on the surface than in the centre layer is reduced with asymmetric rolling.[99,107,108]

After the general texture is determined, further investigation can be made on specific texture components and the ratios between them.[109,110] Throughout the history of metallurgical processes, the material changes texture. Nevertheless, some texture components can originate from the start and cannot be removed. The stability of the texture is also important.[52,73,111]

9 MECHANICAL PROPERTIES

The general purposes of asymmetric rolling are presented to improve the weak mechanical properties of the chosen material.[112] For example, the toughness wants to be improved with asymmetric rolling for HSLA steel[32] as well as a superior combination of strength and ductility at HEAs.[85] The most stress was therefore directed towards improving the formability of aluminium alloys.[82] At the same time, the increase of the strength and hardness was observed with asymmetric rolling. Due to problems with curvature of the workpiece (ski effect), rolling with more passes is difficult. The idea is to use asymmetric rolling only for the last rolling pass and so create better mechanical properties.[113]

9.1 Strength and hardness

Tensile and yield strength have reached higher values with asymmetric rolling, with either the same or even higher strain. The improvement of the properties is, as well as grain sizes and textures, influenced by the deformed material and the asymmetric rolling type.[11,36] In **Figure 13** the stress-strain curves for symmetric rolling and asymmetric rolling types with different speeds of the rollers are presented. It is noticeable that the tensile stresses are more than 50 MPa higher during asymmetric rolling than during symmetric rolling. It is also important to note, that with the highest factor of asymmetry, the tensile strength is not the highest.[114] This can be a consequence of the maximum achieved shear stress and strain components.[9] The hardness value is not as important as is its evenly distributed throughout the cross-section of the workpiece. With asymmetric rolling, higher strains were achieved, with the same set roll gap and consequently also a higher hardness.[79,90]

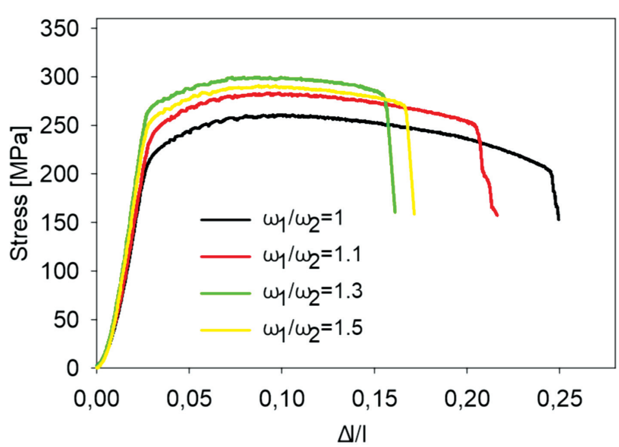

Figure 13: Stress–strain curves for symmetric and asymmetric rolling[114]

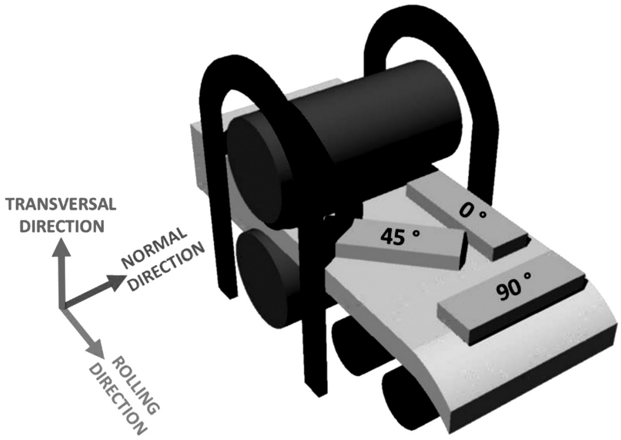

Figure 14: Schematic presentation of asymmetric rolling and the sample directions for the mechanical properties

9.2 Formability

To determine the formability, the Erichsen cupping test for thin samples or plastic strain ratio test for thicker samples are performed. Besides the general deep drawability, the anisotropy is very important. That is why the properties need to be measured in different directions. The dependence of the deep drawability and anisotropy can be expressed with the Lankford factor (R), which is a combination of the elongation and shrinkage of the tested sample. According to the mentioned factor, the normal anisotropy ($\overline{R}$) can be calculated with the Equation (10):

$$\overline{R}=\frac{R_0+2R_{45}+R_{90}}{4} \tag{10}$$

and the planar anisotropy ΔR with the equation:

$$\Delta R=\frac{R_0-2R_{45}+R_{90}}{2} \tag{11}$$

where R_0, R_{45}, and R_{90} are the Lankford factors in different directions according to rolling the direction (**Figure 14**). With asymmetric rolling and texture heterogeneity, the value increases and the ΔR value decreases.[64,82,115–117]

10 SIMULATIONS

Nowadays, computer modelling and simulating makes possible almost anything. Asymmetric rolling is no exception.[118] Simulations of the temperature[119] and mechanical[120] different rolling processes can save a lot of time and reduce the costs of laboratory investigation. With the simulation of asymmetric rolling it is possible to predict the ski effect,[70,71] microstructure,[42] texture[113,121] and mechanical properties.[53] However, many simulated asymmetric processes are backed up with experimental works,[115,122–124] but the real industrial conditions with all the impact factors are very unlikely to be taken into account.[125–127] That is why the results of asymmetric rolling simulations are staying for now as only very good approximations.

11 CONCLUSIONS

Asymmetric rolling is a specific metal-forming process divided into different types regarding the velocity of rollers, the rollers' geometry and the friction changes, as directly influenced parameters. Deliberate asymmetry in the rolling process can be created with different rotation speeds of the rollers, different diameters of the rollers, a single-drive roller and with differently lubricated roller surfaces. Besides the listed options, the asymmetric rolling includes combinations of basic methods and a wide range of special asymmetric rolling types.

The behaviour in the deformation zone is, with asymmetric rolling, different than with symmetric (conventional) rolling. The delay of neutral points creates additional areas between the entry and exit zone, where the larger shear forces, strains and stresses appear. The deformation zone has an effect on the technical parameters, such as the rolling force and the torque. Especially the rolling force reduction is distinguished with asymmetric rolling, as it has an additional option to influence the reduction and strain during the technological process. Higher achieved strains with asymmetric rolling enable fewer passes in the rolling schedule and as a consequence contributes to an improvement of the rolling process' economy. The bending of the workpiece during rolling, also known as the ski effect, presents a major problem for the widespread use of asymmetric rolling in industry because it can cause damage to the rolling mill.

With asymmetric rolling, different mechanical properties can be improved due to significant microstructure changes. Grain size refinement is most often presented as the main advantage of asymmetric rolling in comparison with symmetric rolling, as the pronounced refinement almost always appears with a higher factor of asymmetry. The higher achieved tensile strength, yield strength, hardness and elongation are closely related to the microstructure changes with asymmetric rolling. The changes and differences in the crystallographic texture are directly connected to the improved formability and decreased anisotropy. The heterogeneity of the texture is a desired phenomenon and is due to more shear texture components, easier to reach with asymmetric rolling than with symmetric rolling.

Despite the adjustability of asymmetric rolling simulations, where the technological and mechanical properties can be predicted in the details, the reality from industry rolling is still overlooked in a lot of aspects.

Asymmetric rolling represents many different advantages and improvements of material properties, beneficial to the metal-forming industry, but the problem of its implementation and realisation already exists for several decades. The primary challenges are in mechanical engineering to solve the problems with appropriate construction of rolling mills in industry for asymmetric rolling.

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REPUBLIKA SLOVENIJA
MINISTRSTVO ZA IZOBRAŽEVANJE, ZNANOST IN ŠPORT

MARTIN
MODELIRANJE TERMOMEHANSKEGA PROCESIRANJA ALUMINIJEVIH ZLITIN ZA VRHUNSKE IZDELKE

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