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INVESTIGATION OF THE EFFECT OF SKIN-PASS ROLLING ON THE FORMABILITY OF LOW-CARBON STEEL SHEETS

PREISKAVA UČINKA DRESIRNEGA VALJANJA NA PREOBLIKOVALNOST MALOOGLJIČNE JEKLENE PLOČEVINE

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In the present survey, the effects of skin-pass elongation and cold-rolling reduction on the formability parameters are studied. For this reason, three sets of samples, including those from industry and laboratory, were evaluated. In the first set, samples with different hot-rolling conditions were submitted to the same amount of skin reduction and their final mechanical properties were compared. In the second set, samples with similar conditions were tested with different amounts of laboratory cold reduction after full annealing and, finally, in the third set, fully annealed samples went through different amounts of industrial elongations in a skin-pass line. The results showed that skin reduction has a significant effect on the work-hardening coefficient and it should be kept at the minimum value required to prevent the yield-drop phenomenon. This value was observed to be around 0.5 % for St14 sheets with a thickness of 0.7 mm.

Keywords: ferritic steels, plastic behavior, destructive testing, cold rolling

Preiskovan je bil učinek raztezka in redukcije prereza pri hladnem preoblikovanju na parameter preoblikovanja. Zato so bile ocenjene tri skupine industrijskih in laboratorijskih vzorcev. V prvi skupini so bili v različnih razmerah vroče valjani vzorci dresirno valjani z enako redukcijo, primerjane pa so bile tudi njihove končne mehanske lastnosti. V drugi skupini so bili preizkušeni laboratorijski vzorci z različnimi stopnjami hladne redukcije po predhodnem mehkem žarjenju, v tretji skupini pa mehko žarjeni vzorci izpostavljeni različnim stopnjam raztezka na industrijski liniji za dresiranje. Rezultati so pokazali, da ima redukcija pri dresiranju pomemben vpliv na koeficient hladnega utrjevanja, ki naj bi imel najmanjšo vrednost, da bi se preprečil pojav zmanjšanja plastičnosti. Ugotovljeno je bilo, da je pri pločevini iz jekla St14 z debelino 0,7 mm ta vrednost okrog 0,5 %.

Ključne besede: feritna jekla, plastičnost, porušni preizkusi, hladno valjanje

1 INTRODUCTION

Complex stamping is an important stage in forming automotive body parts and various other products. The steel industry has made many attempts to enhance the quality of their products so that they would lead to easier and faster metal-forming processes. The formability is defined as the resistance of a material to necking and thinning in the thickness direction. The former is known to be related to the work-hardening exponent (n) and the latter to the average plastic-strain ratio (r).[1,2] Drawability, on the other hand, is the ability of a material to easily flow in the plane of the sheet without thinning in the thickness direction, and stretchability represents the ability of the material to resist localized necking.[3,4] In a combined forming operation, r, the normal anisotropy and n, the work-hardening coefficient can be representatives of the drawability and stretchability, respectively. They are obtained with a uniaxial tensile test. Industrial steel sheets with typical values of ($\bar{r}$) in the range 1.6–2.0 and n in the range 0.22–0.24 are known as deep-drawing-quality (DDQ) products.[5]

In recent years, the effects of process conditions and metallurgical microstructure on the quality of low-carbon steel sheets have been studied by mathematical models that use experimental observations as their database. The formability is affected by all the process parameters, such as hot rolling, annealing and the skin-pass conditions.[6,7] Numerous studies have been published regarding the influence of the processing parameters on the microstructure and formability of low-carbon steel.[8–10] However, little has been published on the effect of the skin-pass parameters on the formability.[11]

Skin pass or temper rolling is the last stage in thin-strips production, introducing a small plastic strain in the sheet to bypass the non-uniform deformation region and erase the yield-point jogs. It also improves the flatness of the strip and makes a certain surface roughness and smoothness.[12] The reduction percentage of temper rolling has a significant effect on its mechanical properties. Therefore, the preset of the reduction percentage is restricted not only by the flatness and the surface roughness of the strip steel, but also by the mechanical properties. The mechanical properties of low-carbon steels are influenced by a small strain processing treatment.[13,14] But the effects of a little cold strain and the reduction percentage of skin pass on the formability parameters of steel sheets still need to be investigated. This important issue is the purpose of the present study.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

Three kinds of samples were used in this study. The chemical composition of each is shown in **Table 1**. The first set, prefixed by A from 1 to 5, had a different Al-to-N ratio and coiling temperature (CT), as shown in **Table 1**. All of them received the same amount of 0.7 % industrial skin reduction and their properties were measured before and after the skin-pass process.

The effect of the skin-pass strain on the final formability of the sheets was studied in set B. For this reason, different amounts of cold reduction were applied using a laboratory rolling machine on 40 cm × 60 cm samples obtained from a longitudinal section of a coil after an industrial box anneal and near each other. Again, their properties were measured before and after the skin pass (**Table 2**).

It should be noted that there are two operations in skin pass rolling: a stretching that is applied using a tension leveler and a compression applied from rolls. As it was not possible to apply the stretching load on laboratory skin rolling, a separate set of samples, set C, was imposed on a different amount of reductions using an industrial skin machine to investigate the effect of the real skin process on the final properties.

2.2 Experiments

Standard uniaxial tensile tests were carried out on the samples in three directions, i.e., 0°, 45° and 90°, corresponding to the rolling direction, to obtain the strength and ductility of the specimens as well as the r and n coefficients. The normal anisotropy was calculated according to the equation:

$$\bar{r} = (r_0 + 2r_{45} + r_{90})/4 \tag{1}$$

$\bar{n}$ was also calculated in a similar way to reach an average value.[2]

The average grain sizes (d) of the samples were measured according to ASTM E112-96 (Jeffries method) and the optical micrograph of the samples was prepared by a standard metallographic technique. As the grain structure in low-carbon steel sheets after cold rolling and box annealing is generally pancaked, the aspect ratio of the elongated grains was also evaluated using measurements of the large and small diameters of the grains, separately.

3 RESULTS AND DISCUSSION

3.1 Effects of the process parameters on the final properties under similar skin-pass conditions

The magnitudes of $\bar{r}$ and $\bar{n}$ for the samples of set A, before and after the skin pass, are illustrated in **Figure 1**. Although $\bar{r}$ does not demonstrate any large change before and after the skin pass, the variations of $\bar{n}$ are drastic, clearly showing a significant decrease after the treatment.

In accordance with **Figure 1a**, the skin pass does not have any significant effect on $\bar{r}$. This parameter is mostly affected by grain orientation or texture.[2] It has been shown that high $\bar{r}$ values are displayed by materials that have a high proportion of grains oriented with {111} planes parallel to the sheet plane. The {111} fiber texture is particularly beneficial for imparting good deep drawability.[15] It has also been shown that the morphology of cementite particles and the precipitation of fine AlN precipitates control the texture of low-carbon steel

Table 1: Chemical composition of the investigated samples in mass fractions, w/%
Tabela 1: Kemijska sestava preiskovanih vzorcev v masnih deležih, w/%

NUM	w(C)	w(Si)	w(Mn)	w(Al)	w(N)/(μg/g)	w(Al)/w(N)	CT/°C
A1	0.045	0.009	0.209	0.049	19	25.7	560
A2	0.049	0.01	0.204	0.047	30	15.6	560
A3	0.039	0.009	0.209	0.049	19	25.7	620
A4	0.05	0.01	0.0220	0.055	58	9.4	625
A5	0.05	0.01	0.220	0.055	58	9.4	625
B	0.036	0.012	0.27	0.043	25	17.2	–
C	0.034	0.009	0.215	0.045	35	12.8	–

CT – Coiling Temperature

Table 2: Normal anisotropy, work hardening values, applied reduction and grain size and aspect ratio for the samples in set B
Tabela 2: Normalna anizotropija, vrednosti utrjevanja pri preoblikovanju, uporabljena redukcija, velikost zrn in razmerje širina proti debelini vzorcev iz skupine B

NUM	Cold reduction (%)	$\bar{r}$	$\bar{n}$	Grain size d/(μm)	Aspect ratio
B0	0	1.60	0.24	26	2.26
B1	2.5	1.60	0.19	24	2.9
B2	3.8	1.62	0.19	26	3.1
B3	4.8	1.59	0.15	27	3.6

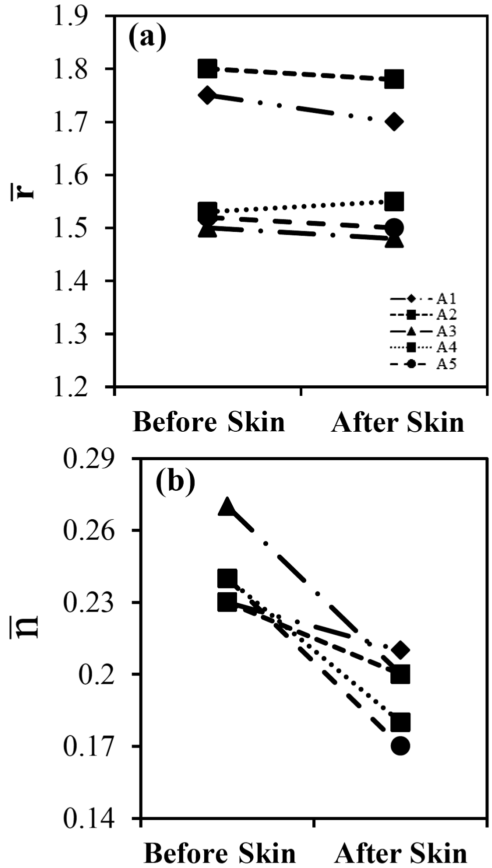

Figure 1: Variation of: a) $\bar{r}$ and b) $\bar{n}$ before and after the skin-pass rolling for samples in set A

Slika 1: Spreminjanje: a) $\bar{r}$ in b) $\bar{n}$ pred dresirnim valjanjem vzorcev iz skupine A in po njem

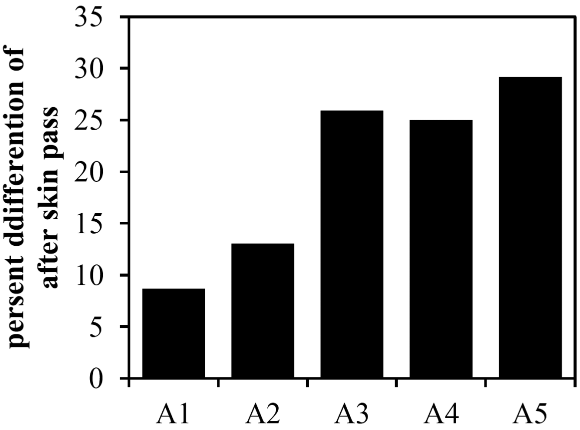

Figure 2: Variation percentage of $\bar{n}$ after skin pass in the samples of set A

Slika 2: Spreminjanje deleža $\bar{n}$ pri dresirnem valjanju vzorcev iz skupine A

sheets.[15,16] The most important process parameters affecting these microstructural features are hot and cold.

The rolling parameters and subsequent annealing parameters, such as the heating rate and soaking time are important.[6,10] The most important microstructural effect exerted by the limited strain in skin-pass rolling, except the very small strain near the surface, is releasing dislocations from short-range local locks of carbon and nitrogen atoms and eliminating the yield drop and heterogeneous deformation.[8,9] Therefore, cold deformation due to the skin-pass process has a slight effect on the volume fraction of {111} fiber and its influence on $\bar{r}$ is almost negligible.[1]

Figure 1b implies that for all samples of set A, $\bar{n}$ is decreased considerably after the skin-pass process.

The variation percentage of $\bar{n}$ in each sample is shown in **Figure 2**. It can also be seen that the drop value is not the same for all the samples, varying in the range of 8.7 % to 30 % for different samples. This reduction is due to the direct relationship between the work-hardening coefficient and the microstructure variations. The relationship between the microstructure and the work-hardening coefficient can be explained by Eq 1, which was first expressed by Antoine:[8,9]

$$n = 0.450 - 0.001(\sigma_{\mathrm{P}} + \sigma_{\mathrm{SA}} + \sigma_{\mathrm{GB}} + \sigma_{\mathrm{PCT}} + \sigma_{\mathrm{F0.2}}) \quad (2)$$

The stresses in this equation are the strengthening contribution of Peierls (σ_{P}), the solid solution (σ_{SA}) (both affected by the chemical composition), the precipitates (σ_{PCT}), the grain boundaries (σ_{GB}) and the dislocation density ($\sigma_{\mathrm{F0.2}}$). The above equation shows that all the mentioned microstructural factors affect n directly. Among them, the dislocation density and the grain-boundary characters (in the form of the shape and the aspect ratio) may be changed during the skin-pass rolling, while the chemical composition's and the precipitates' contributions remain unchanged.

The study of the grain characteristics in these samples implied a very negligible difference between the grain elongations. Therefore, the only influential microstructure factor would be the variation of the dislocation density in the various samples.

Among the microstructural parameters that may affect the dislocation density during cold work, the precipitates are of paramount importance. They can play the role of an obstacle preventing dislocation movement and increase the work-hardening rate. Hence, the work-hardening coefficient decreases. This can be explained better by referring to the results of Antoine's work. **Figure 3** illustrates the dislocation density calculated for the samples with a different volume percentage of TiC precipitates after 0.02 % strain. These data are derived from the results of Antoine's work. It can be seen from the figure that by increasing the volume fraction of the precipitates, the dislocation density is increased and n is decreased.[8,9]

The difference in the amount of work hardening coefficient for the samples in set A, therefore, may be attributed to the volume fraction of the precipitates before the skin pass, which in the case of St14 steels, and in absence of carbide-forming elements like Ti, are mostly AlN particles. The volume fraction and the size of the AlN precipitates are influenced by various pro-

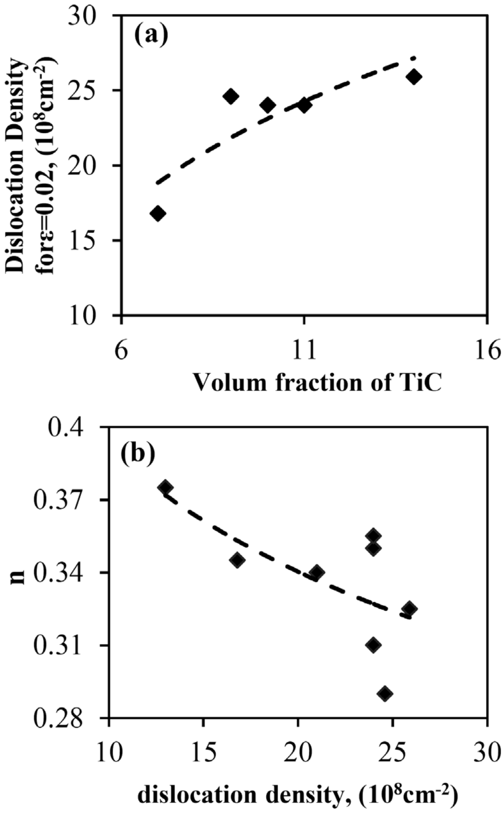

Figure 3: The dependence of: a) dislocation density on volume fraction of TiC precipitates and b) work-hardening coefficient on the dislocation density, calculated and drawn from Antoine's results[9,10]
Slika 3: Odvisnost: a) gostote dislokacij od volumenskega deleža izločkov TiC in b) koeficient utrjevanja pri hladni predelavi na gostoto dislokacij, izračunano in vzeto iz rezultatov Antoina[9,10]

duction parameters, with the most important ones being the cooling rate and the coiling temperature after hot rolling,[10] and the heating rate during annealing.[1] The reported CTs for the samples in set A are shown in **Table 1**. It is clear that A3, A4 and A5 experienced the highest CT.

Coiling above 600 °C can promote the precipitation of AlN precipitates and affect the microstructural features during the following annealing process.[10] As all the samples in set A have experienced the same annealing conditions, it can be concluded that the differences in the CT have led to a different amount of work-hardening coefficient due to the different volume fraction of AlN under the same conditions of the skin-pass process.

3.2 Effect of experimental cold reduction on the formability parameters of fully annealed samples

Figure 4 shows the dependences of $\bar{r}$ and $\bar{n}$ on the percentge of cold reduction (after full annealing) for the samples in set B. It is implied that while increasing the cold reduction the percentage does not have any obvious effect on $\bar{r}$ in the examined range,[1] it decreases $\bar{n}$ in a discernible manner. For instance, in the case of the sample without cold work, the amount of $\bar{n}$ is almost 0.25,

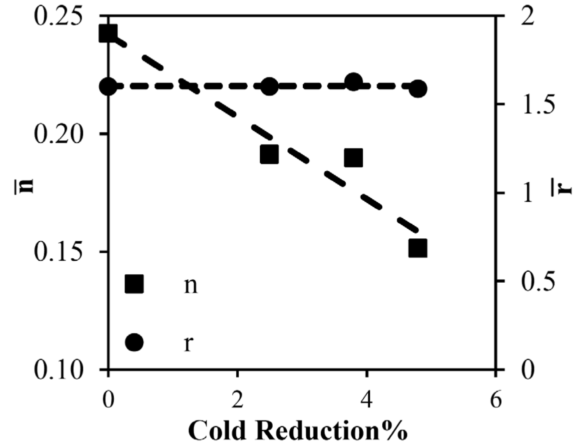

Figure 4: Variation of $\bar{r}$ and $\bar{n}$ with cold reduction in samples of set B
Slika 4: Spreminjanje $\bar{r}$ in $\bar{n}$ z redukcijo v hladnem vzorcev iz skupine B

whereas it reaches 0.15 after 4.8 % cold reduction. As mentioned in the previous section, the variations of $\bar{n}$ with the percentage of cold work may be related to variations in the dislocation density. On the other hand, the slip distance of dislocations, which is in relation to the grain size, is expected to affect $\bar{n}$ due to the increasingly homogeneous strain region.[8,9] To examine this parameter, the variations of the grain size with applied elongation were characterized and illustrated in **Figure 5**.

As can be seen, the variation of grain size with increasing cold-work percentage in the examined range is not considerable. However, the grains' aspect ratio is increased in proportion to cold reduction percentage, due to the elongation along the rolling direction. This confirms that the most influential factor in decreasing $\bar{n}$ with cold reduction is increasing the dislocation density. It suggests that the limitation of cold reduction in the skin-pass rolling can prevent an excess drop of $\bar{n}$. However, the amount of the reduction should be in such a range that would guarantee the elimination of the heterogeneous deformation region (yield drop phenomenon).

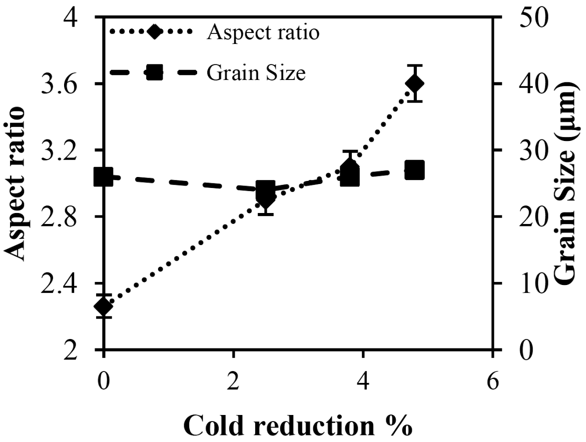

Figure 5: The relation of grain sizes and their aspect ratio to cold reduction in the samples of set B
Slika 5: Odvisnost velikosti zrn in njihovega razmerja širina-debelina, pri hladni redukciji vzorcev iz skupine B

3.3 Effect of skin-pass elongation on the formability properties of industrial samples

The effects of the skin-pass elongation on the $\bar{r}$ and $\bar{n}$ values in the samples of set C are shown in **Figure 6**. These samples had the same chemical composition (**Table 1**) and the same processing conditions, except the amount of elongation in the skin-pass step.

As can be seen in **Figure 6**, and as can be expected from the results of the previous section, the elongation percentage of the skin pass does not have any influence on $\bar{n}$, whereas it severely decreases $\bar{n}$. It should be noted that although the strain path in experimental skin rolling (compression from rolls and the tension applied on the whole line between the feeding and coiling rolls) is different from the laboratory rolling experiments (just compression from the rolls) in the previous section, it does not have any influence on the variation of the work-hardening coefficient. This is due to the fact that $\bar{n}$ is mostly affected by the dislocation density, which is similar in the experimental range of strain in both laboratory and industrial experiments.

Figure 6 shows that the elongation percentage of 0.5 % in the skin pass has led to the highest amount of work-hardening coefficient. Laboratory tests showed that lower amounts of elongation percentage do not prevent the occurrence of yield-drop phenomenon. It may be concluded that the most suitable elongation percentage in the skin-pass step for the sheet thickness studied (0.7 mm) is 0.5 %.

4 CONCLUSIONS

In this study, low-carbon steel sheets were investigated from a formability point of view.

The following results were obtained. The work-hardening coefficient is mostly affected by the dislocation density. Any microstructural feature that can increase the dislocation density can decrease $\bar{n}$. While the skin-pass reduction after full annealing does not have any large effect on $\bar{r}$, it may change $\bar{n}$ drastically. Therefore, the limitation of skin reduction to a minimum value is required to prevent yield drop, which is an important process parameter that can preserve $\bar{n}$ at an appropriate level after it reaches its maximum value during the annealing process. This value was observed in this study to be around 0.5 % for St14 sheets with a thickness of 0.7 mm.

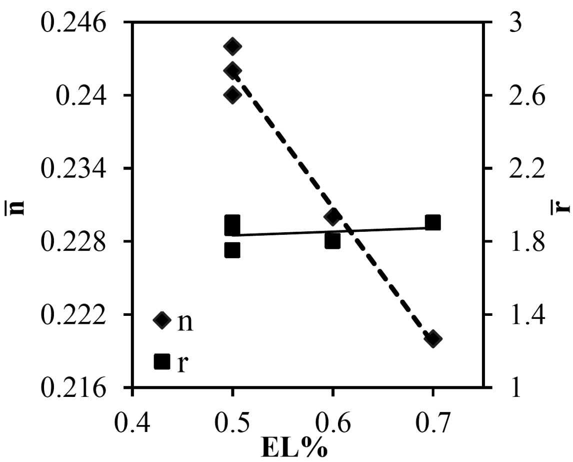

Figure 6: Variation of $\bar{r}$ and $\bar{n}$ with elongation percentage in skin-pass rolling for samples in set C

Slika 6: Spreminjanje $\bar{r}$ in $\bar{n}$ z deležem raztezka pri dresirnem valjanju vzorcev iz skupine C

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