EFFECT OF PROCESSING ROUTE ON MICROSTRUCTURE AND MICROHARDNESS OF LOW-CARBON STEEL SUBJECTED TO DRECE PROCESS

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https://doi.org/10.37904/metal.2021.4120

Abstract

Presented paper reports the effect of the processing route on the microstructure and microhardness in the cold rolled low-carbon sheets processed by dual rolls equal channel extrusion (DRECE). The DRECE process was repeated up to four passes in two processing routes, called routes A and C. As the number of passes increased, the heterogeneous evolution of microhardness and microstructural heterogeneities between the core and surface regions gradually became intensified in both processing routes. The results showed that the DRECE method is a powerful method for processing the sheets with gradient structure and enhanced utility properties. Therefore, it appears that the proposed method has a great potential to a wide range of industrial applications.

Keywords: SPD, low-carbon steel, DRECE, microhardness, microstructure

1. INTRODUCTION

Severe plastic deformations (SPD) represent a significant possibility to increase the values of mechanical properties due to the fragmentation of the original microstructure to the level of an ultra – fine grained structure (UFG). This is an intensively researched area of research with great potential for application in the manufacturing sphere. In particular, the possibility of continuous processes appears to be promising for the production of highly stressed components or products for applications in extreme conditions [1].

The principle of continuous SPD methods is based on the conversion of the principle of the ECAP method into a continuous form. Currently, there are a large number of continuous SPDs, which show interesting results, especially in terms of refining the structure and increasing the level of mechanical and physical properties. Among the most promising are the Single Roll Angular Rolling (SRAR) [2] or Equal Channel Angular Rolling (ECAR) [3] methods, which enable the preparation of UFG structures in massive samples of large lengths.

1.1. Principle of DRECE method

The DRECE method (Dual Rolls Equal Channel Extrusion) [4-5] is based on the principle of angular extrusion through an equilateral channel using contact friction between the extruded blank, in the form of a sheet metal strip, and feed rollers. Based on the generated friction force, the sheet is continuously extruded into a special forming tool, where it is intensively deformed by shear deformation as it passes through the deformation zone. As a result of the accumulation of deformation, microstructural changes occur, which lead to an increase in the strength characteristics of the extruded sheet. A schematic representation of the SPD method of DRECE is shown in **Figure 1**.

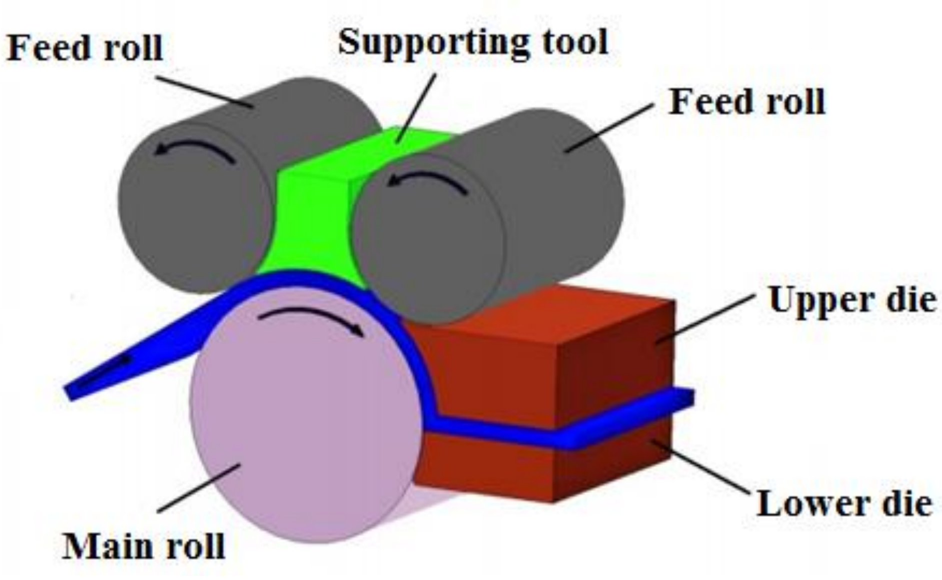


Figure 1 Schematic illustration of DRECE device [4]

Due to the technological aspects of DRECE extrusion, the deformation is unevenly spread over the thickness of the sheet metal. From the results presented in [4], the largest deformation values are localized in the surface area of the extruded belt, where the deformation value is approximately 0.71 and this value in the thickness direction decreases to 0.45. Heterogeneous deformation leads to uneven grain softening due to the application of the forming process and at the same time negatively affects the resulting mechanical properties of the forming sheet. An important factor is a detailed analysis of the distribution of microstructure changes in the extruded sheet metal, as these are directly involved in the resulting properties of the sheet metal.

2. INVESTIGATION PROCEDURES

The work is focused on analyzing the influence of the deformation rout when pushing a sheet metal strip made of commercially produced DC01 steel with dimensions of 2 x 58 x 2000 mm. The chemical composition of the sheet metal strips tested is given in **Table 1**.

Table 1 Chemical composition of steel DC01 (wt. %)

Element	**C**	**Mn**	**Si**	**P**	**S**
(wt. %)	0.040	0.250	0.010	0.009	0.006

Before extrusion using the DRECE method, lubricant (based on MoS_2) was applied to the sheets to minimize friction in the deformation zone of forming tools. Experimental extrusion was carried out at room temperature and constant forming conditions. Extrusion speed 5 $mm \cdot s^{-1}$, pressures on the front cylinder 50 bar and on the rear cylinder 150 bar. Two deformation route strategies were used during extruding, namely type A (sheet metal does not overturn between individual passes) and type C (the sheet metal is rotated 180° between each pass). Sheets were pushed through a maximum of 4 passes using both types of deformation routes.

The analysis of the effect of the applied deformation pathway in DRECE forming on the change of microstructure was performed on the NEOPHOT 21 optical microscope with OLYMPUS GX51. Detailed analysis of the microstructure was carried out on TEM. TEM images were captured utilizing FEI TECNAI G transmission electron microscope operating at 200 kV. The microhardness was measured after the thickness of the extruded sheet using the Hanemann automatic micro-hardness device.

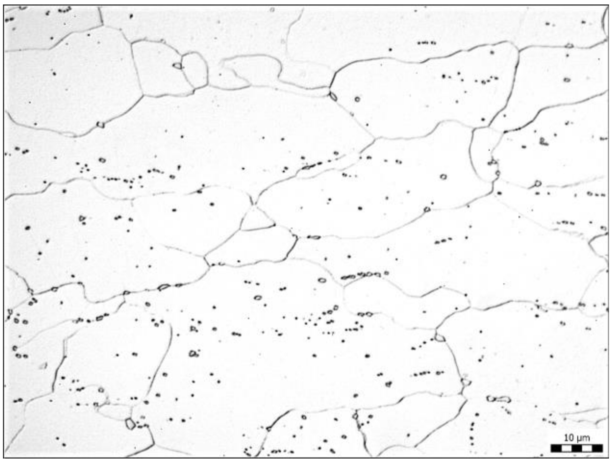
3. INVESTIGATION RESULTS

3.1. Microstructural characterization

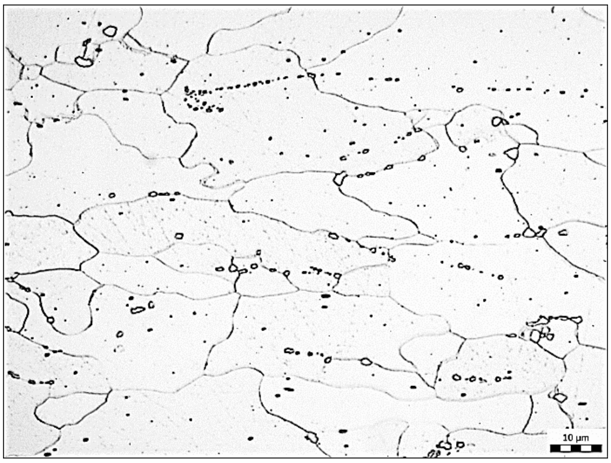
Images of the DC01 steel microstructure depending on the processing status are given in **Figure 3**. Depending on the processing, the microstructure of all the samples analyzed was similar, fairly uniform, consisting of polyedral grains of ferrite and cementite, expelled both by borders and inside grains. Depending on the processing, slight stretching of grains in the direction of extrusion by the DRECE method was observed on the longitudinal cut-outs.

The samples after the 2nd pass showed clear signs of deformation mainly in the subsuasive part, and with the increasing number of passes (4th pass) the deformation was noticeable even at greater distances from the surface of the extruded sheet.

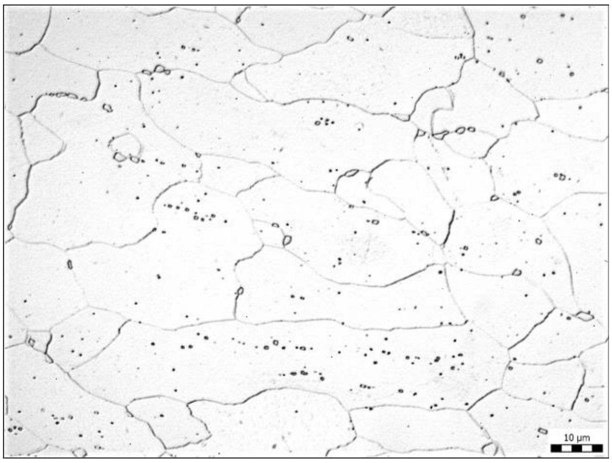
When comparing the influence of the two types of deformation routes under study, no significant character difference was observed on the microstructure of the DC01 sheet metal strip.



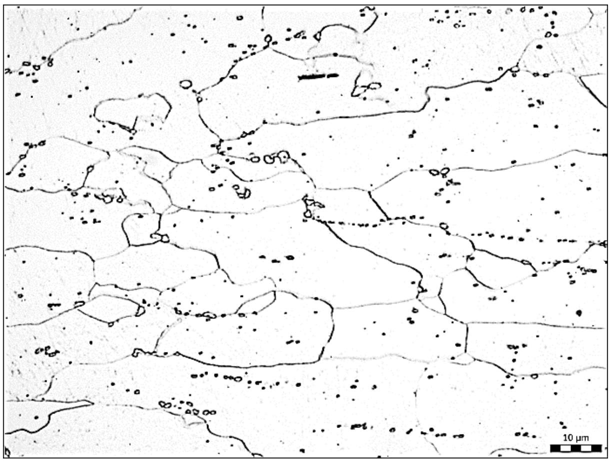
2nd pass (route A)



2nd pass (route C)



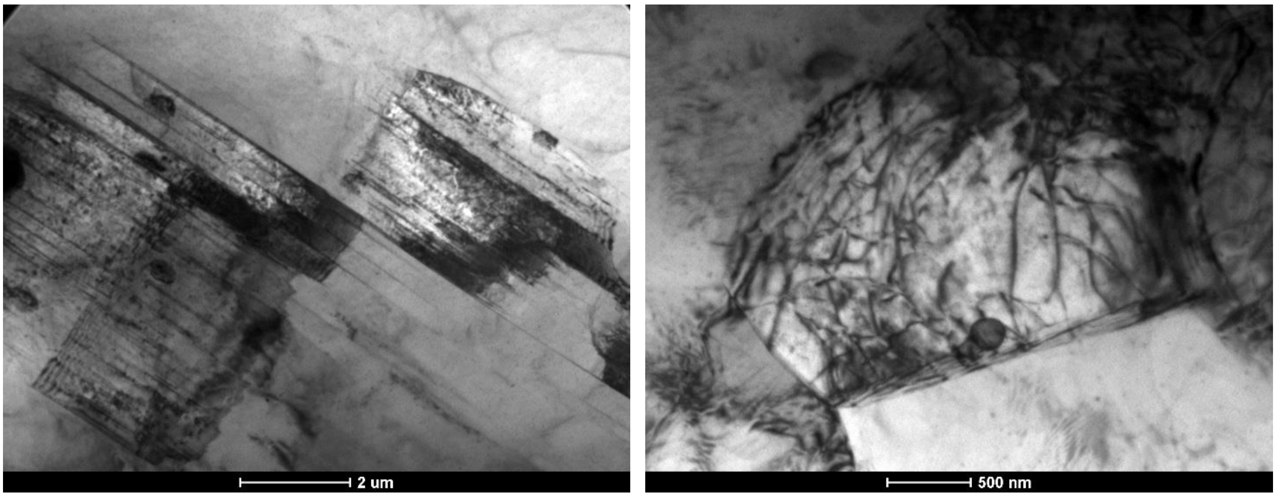
4th pass (route A)



4th pass (route C)

Figure 3 OM images of DC01 steel

TEM images (**Figure 4**) show the detailed state of the DC01 steel microstructure after DRECE processing. Due to DRECE extrusion, there was a visible increase in the density of dislocations accumulated in shear deformed ferrite grains (**Figure 4a**), but with minimal effect on fragmentation of the original grain. However, the occurrence of dislocation cells, probably separated by a low-angle grain boundaries (LAGB's), can be observed. The original grain boundaries are preserved with an increasing proportion of LAGB's in locally softened parts of the microstructure. With the increasing number of passes, it is noticeable that due to the accumulation of deformation energy, dislocations have been reordered into regular structures (**Figure 4b**).



a) **b)**

Figure 4 TEM images of deformed DC01 sheets: after 1st pass (a) and after 4th pass

3.2. Microhardness evolution

The way to monitor the effect of DRECE forming on the uniformity of the distribution of mechanical properties is to measure microhardness after the thickness of the extruded sheet metal. For the analysis, an inductor was used to measure HV with a load of 0.1 kg for 15 seconds.

Figure 5 graphically shows the course of microhardness HV0.1 depending on the distance from the top surface of the sheet metal, extruded by the DRECE method when using the deformation route A (without rotation). Based on the presented process, it can be concluded that due to DRECE forming, higher hardening values were achieved mainly in the subsuasive parts of the analyzed sheet metal samples. As the number of passes increased, the average value of microhardness increased from 127 HV0.1 to 165 HV0.1 (after both 3rd and 4th passes), with values higher in the area below the upper surface, approximately 181 HV0.1. It is clear that when using the deformation route A, it is necessary to calculate with an uneven distribution of microhardness values, which corresponds to the theoretical conclusions presented in [5].

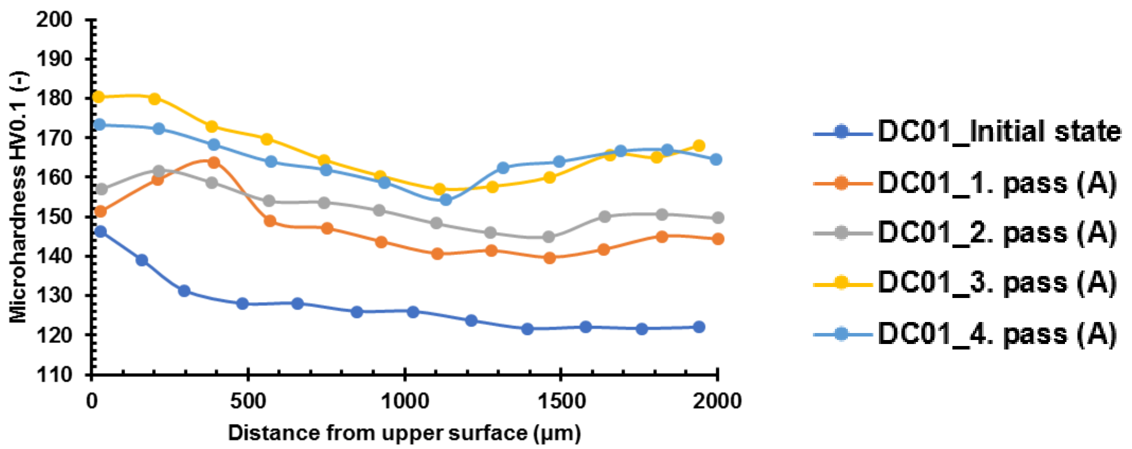


Figure 5 Microhardness in thickness distribution in DC01 sheets processed by DRECE method, route A

By measuring the distribution of micro-hardness after sheet thickness, extruded by the DRECE method using the deformation route C **(Figure 6),** when the sheet is rotated 180° between individual passes, it demonstrated the effect of the DRECE method on increasing micro-hardness. From the original average value of 127 HV0.1, an average value of 181 HV0.1 (after the 4th pass) was achieved with a maximum achieved value of 193 HV0.1, which was achieved in the surface area of the sheet metal after the 4th pass. Microhardness over thickness shows an even distribution of micro hardness between the two ends of the sheet metal. This course can be attributed to the influence of rotation between individual passages, thus evenly dicing the applied deformation and thus the resulting values of microhardness after the thickness of the extruded sheet metal.

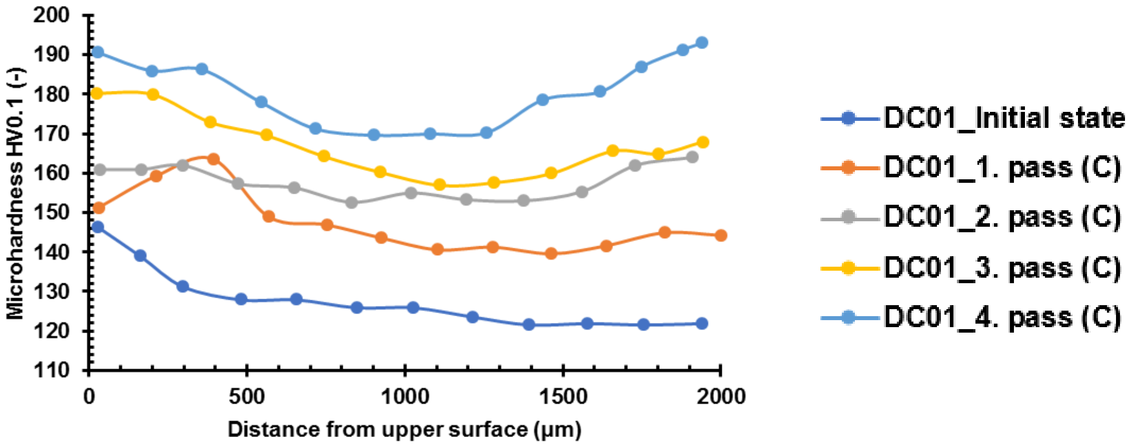


Figure 6 Microhardness in thickness distribution in DC01 sheets processed by DRECE method, route C

4. CONCLUSION

The positive influence of the DRECE method on the change in the nature of the microstructure and the distribution of micro-hardness values after the thickness of the DC01 sheet metal strip has been demonstrated.

Detailed analysis of the state of the microstructure depending on processing has shown that the dominant phenomenon is deformation hardening due to the accumulation of dislocations along the boundaries of the original grains and with an increasing number of passes even in the middle of deformed grains. Depending on the deformation routes analyzed, no significant difference was observed between the two types of deformation routes compared. A visibly higher degree of deformation was achieved in the subsuasive layers, and as the number of passes increased, the deformed layer shifted towards the center of the sheet thickness. No significant change in grain size was observed, which depending on the number of passes, remained the same as in the default state, i.e. according to ČSN EN ISO 643, the grain size G9 (surface area) was determined and locally at higher passes G8.5 in the middle of the thickness of the samples analyzed. Detailed analysis at TEM demonstrated the occurrence of accumulation of dislocations in deformed grains, which was more common in the subsuasive parts of the sheet metal. With an increasing number of passes, reordering of dislocations into regular substructures, separated by a low-angular boundary, was observed. It can be concluded that depending on the number of passes by the DRECE device, there is a gradual change in the nature of the microstructure with the assumption of further development of subsupply, separated by a large-angle boundary, which is the main indicator of the required fragmentation of the original grain.

It is expected that the positive effect of the DRECE method used on the achieved average microhardness values HV0.1 has been demonstrated, with these values increasing to 165 HV0.1 (deformation route A) and 181 HV0.1 (deformation route C) respectively. In comparing the microhardness values after the thickness of the samples analyzed using the deformation route A, an unevenness was observed between the two sheet surfaces and the centre of thickness, where higher microhardness values were achieved on the top surface of the sheet metal. In the direction of thickness, these values decreased, with a partial emanation of the distribution of microhardness as the number of passes increased, but the different character was maintained. In the case of samples that were processed using the deformation route C, this nature of the microhardness distribution was not significant, as was the case with route A used. Only minimal deviations could be observed between the edges of the sheet metal and the centre of thickness, but these were already apparent by default, i.e. from production.

ACKNOWLEDGEMENTS

Results in the contribution were achieved at solving of specific research project No. SP2021/104 with the name of "Research and Development in Welding, Forming, Surface Treatments of Engineering Materials and Management of Engineering Production" solved in year 2021 at the Faculty of Mechanical Engineering of VSB – Technical University of Ostrava and project No. 8JPL19035: "Influence of SPD Process on Structure and Mechanical Properties of Al-Si Composites and Ti Alloys".

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