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EFFECT OF DEFORMATION AND HEAT TREATMENT ON MICROSTRUCTURE OF WARM ROLLED STEEL IN ALPHA-GAMMA AREA

Omer Beganović
Belma Fakić
University of Zenica, Institute „Kemal Kapetanović“ of Zenica
Travnička cesta 7, Zenica
Bosnia and Herzegovina

Ali Mohammed Ali Mohammedzain
Babekir Ahmed Osman Mohammed
Sudan University of Science and Technology, Materials Research Center
Khartoum
Sudan

Faik Uzunović
University of Zenica, Faculty of Metallurgy and Technology
Travnička cesta 1, Zenica
Bosnia and Herzegovina

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ABSTRACT
In this paper the effect of different heat treatment (recrystallization, spheroidizing and normalizing) processes on microstructure of the steel DC04 intended for deep drawing is presented. The steel is cladded with CuZn10 layers by explosive welding. Since the melting temperature of alloy CuZn10 is significantly lower (melting range 1025-1045 ^oC) then melting temperature of steel DC04 (melting range 1400-1500 ^oC) hot working temperature range of CuZn10 alloy (750-900 ^oC) is significantly lower than normal hot working temperature range of DC04 steel. Because of that the deformation of the steel should be done in alpha-gamma area. This will give a different microstructure compared to the case when hot rolling process is performed in gamma area.

1. INTRODUCTION
Explosion welding is a solid state welding process that can be used for joining metallurgically compatible metals but also metallurgically non compatible metals which are not possible to be joined by any other welding techniques. A weld surface with metallurgical bond between joined materials is produced by controlled detonation of chemical explosive that is placed on cladding metal (flyer plate) [1]. Pressure created by explosive detonation directs flyer plate to the fixed base metal plate resulting in collides of them and bonding at their interface [2]. Because of high pressure produced by explosive detonation the metals at the interface are locally plastically deformed and metallurgically bonded. The pressure has to be sufficiently high and for a sufficient duration of time to achieve the inter-atomic bonds [3]. Between two

metal components an electron-shearing metallurgical bond is created on the way that explosion forces bring metal surfaces into sufficiently close contact that valence electrons can overcome the repulsive forces resulting in sharing of their orbits [4, 5]. Heat-affected zones are no created and there is no diffusion of the atoms of alloying element between joined metals. Also, continuous cast structure between joined metals is not created [4, 5, 6, 7, 8].

The explosion welding process is primarily used for cladding some metals with other metals having better corrosion resistance as in the case of cladding of low carbon steel with copper alloys. It is possible to clad by explosion welding process one or more layers onto one or both faces (sides) of base metal. Since the bonded metals usually have significantly different mechanical and physical properties they will behave differently during plastic deformation. Since the melting temperature of alloy CuZn10 is significantly lower (melting range 1025-1045 ^oC) then melting temperature of steel DC04 (melting range 1400-1500 ^oC) hot working temperature range of CuZn10 alloy (750-900 ^oC) is significantly lower than normal hot working temperature range of DC04 steel [9, 10]. Because of that the rolling of the steel should be done in alpha-gamma area. This will give a different microstructure compared to the cases when hot rolling process is performed in gamma area.

In the case of an ultra low and a low carbon steel, rolling process can be finished in austenite, mixed austenite-ferrite or in ferrite (with small content of pearlite) area (Figure 1) [11]. In the case of the rolling in austenite area (temperature above A_3), depending on temperature control it is possible to achieve recrystallized austenite needed for performing a subsequent controlled cooling or to achieve temperature slightly above the A_3 temperature enabling conditions similar to condition for normalizing heat treatment (normalizing rolling) [11, 12].

In the case three-layers strip rolling with clad CuZn10 layers (on top and bottom of the strip) having limited upper hot working temperature on 900 ^oC, the rolling of the steel as middle layer, should start from a temperature within alpha-gamma area. Depending on chosen temperature the quantity of alpha and gamma phase will be different (Figure 1). In any case if it is needed to perform relatively large height reduction, the rolling process may be done only with a higher number of passes. It means that rolling process cannot be finished in alpha - gamma area because of relatively narrow temperature range. Therefore, the rolling process is prolonged in ferrite-pearlite area, especially when the strip thickness becomes small. So after a decrease of a temperature, the strip should be reheated.

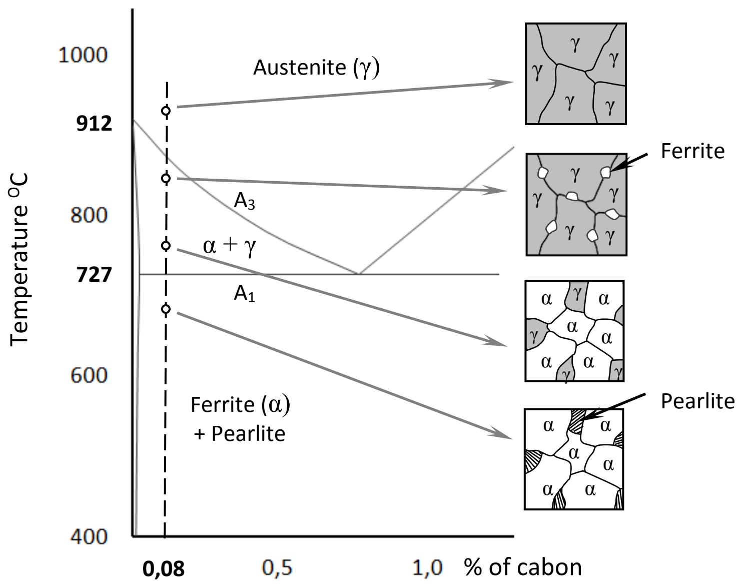

Figure 1. Phase transformation of 0.08% C-steel at slow cooling rate

During this reheating process microstructure formation is determined by a number of interacting metallurgical phenomena, of which ferrite recrystallization, austenite formation and carbon diffusion are the most important [13]. After starting of rolling process the transformation of austenite to ferrite, deformations of ferrite, and diffusion of carbon due to pearlite formation, are the most important processes.

In the case of the rolling in ferrite-pearlite area there is not significant interaction between different metallurgical phenomena. There is only deformation of the ferrite and pearlite. The ferrite is ductile phase and it is deformed easily. The cementite lamellae are extremely hard and brittle therefore they fracture in small pieces during plastic deformation [14, 15]. Fragmentation of cementite lamellae accelerates their spheroidization during the large warm deformation compared to a spheroidization during soft annealing of the undeformed lamellar pearlite [16]. The spheroidization process is controlled by diffusion rate of carbon and the portions of the lamellae must dissolve and that dissolved carbon must diffuse to form a spheroid from the remaining portions of lamellae [17]. If the cementite lamellae are broken in small pieces, the diffusion of dissolved carbon occurres on short distance and the process is faster. The spheroidization process takes several hours (up to 20 hours) in the case of soft annealing of an undeformed lamellar pearlite but in the case of presence of fragmented cementite lamellae, the process is much shorter. The physical mechanism of soft annealing is based on the coagulation of cementite particles within the ferrite matrix with the aim of a reduction of internal energy because of globular cementite within the ferritic matrix is the structure having the lowest energy content of all structures in the iron–carbon system [18]. In the case of a low carbon steel, spheroidization process is performed for improving cold formability of the steels [17, 18, 19].

2. EXPERIMENTAL PROCEDURES

Samples for rolling were three-layers plate obtained by explosive welding. The plates of copper alloy (CuZn10 according to the standard EN 1652) were welded to the plate of low carbon steel (DC04 steel for deep drawing according to the standard EN 10130) on both sides (top and the bottom side) of the steel plate. Chemical composition of the particular layers is presented in Table 1.

Table 1. Chemical composition of the steel DC04 layer and clad CuZn10 layers

Material	Composition in wt.%									
	C	Mn	Si	P	S	Al	Cu	Zn	Pb	Fe
DC04	0.08	0.30	0.03	0.009	0.003	0.023	-	-	-	Rem.
CuZn10	-	-	-	-	-	-	89.9	10.1	< 0.01	< 0.01

The dimensions of the three-layers plate obtained by explosive welding were 1200x2000 mm. Samples (strips) of nominal width 90 mm were cut by water jet from the three-layers plate. The rolling was performed on Light section rolling mill SKET ϕ370 mm from 34.8 mm to 4.3 mm of thickness (8 passes) - Table 2, and Laboratory light section rolling mill ϕ250 mm from 4.3 mm to 2.3 mm of thickness (3 passes) - Table 3. The relative total height reduction for the first eight passes is 87.7%, the relative total height reduction for the last three passes is 46.5%. Cumulative total height reduction for all eleven passes is 93.4%. During rolling process on Light section rolling mill SKET ϕ370 mm (the first eight passes) the rolled strips were reheated on the starting rolling temperature (850 ^{o}C) after each pass while during rolling process on Laboratory light section rolling mill ϕ250 mm (the last three passes) the rolled strips were heated on the different starting rolling temperatures with or without reheating between the individual passes (Table 3). The strips rolled according to data given in Table 2 were used for performing each variant of the rolling presented in Table 3. The temperature after each pass on both rolling mills and for all rolling variants were measured (Figure 2).

Table 2. Data related to the first eight passes of the strip rolling

Rolling mill	Pass number	Cross section dimensions after pass (mm)		Heating regime
		Thickness	Width	
	Staring strip	34.8 x 89.3		Heating on 850 ºC
Light section rolling mill SKET ф370 mm	1.	26.7 x 92.7		Reheating on 850 ºC
	2.	20.5 x 93.9		Reheating on 850 ºC
	3.	14.7 x 96.5		Reheating on 850 ºC
	4.	10.7 x 99.2		Reheating on 850 ºC
	5.	8.2 x 99.7		Reheating on 850 ºC
	6.	6.1 x 99.7		Reheating on 850 ºC
	7.	5.2 x 99.7		Reheating on 850 ºC
	8.	4.3 x 100.4		Reheating on 850 ºC

Table 3. Data related to the last three passes in different rolling variants

Rolling mill	Rolling variant	Pass number	Cross section dimensions after pass (mm)		Heating regime
			Thickness	Width	
Laboratory light section rolling mill ф250 mm	Variant I	Starting strip	4.3 x 100.4		Heating on 850 ºC
		9.	3.7 x 101.0		Reheating on 850 ºC after each pass
		10.	2.9 x 101.7		
		11.	2.3 x 102.3		
	Variant II	Starting strip	4.3 x 100.4		Heating on 850 ºC
		9.	3.7 x 101.0		Without reheating between passes
		10.	2.9 x 101.7		
		11.	2.3 x 102.3		
	Variant III	Starting strip	4.3 x 100.4		Heating on 700 ºC
		9.	3.7 x 101.0		Reheating on 700 ºC before the last (eleventh) pass
		10.	2.9 x 101.7		
		11.	2.3 x 102.3		

For comparison of the microstructural characteristics of the DC04 steel hot rolled from austenitic area with the same steel rolled from alpha-gamma area and the same steel rolled from temperature 700 ºC, one strip with thickness 4.3 mm was rolled from temperature 930 ºC on Laboratory light section rolling mill ф250 mm in three passes with reheating on the same temperature only before the last pass. The strips of all rolling variant are recrystallized on 700 ºC/60 minutes. For microstructural characterization of rolled and heat treated strips corresponding metallographic specimens were prepared. To reveal of the microstructure all specimens were etched by 2% HNO_3.

3. RESULTS

Values of the strip temperature measured after each rolling pass are presented at Figure 2 (totally eleven passes, including the passes of the rolling variant I – Table 3). In the case of the rolling variant II which implies three rolling passes without reheating between them the strip temperature after the last pass was 505 ºC. Starting temperature was 850 ºC. In the case of the rolling variant III which implies reheating the strip on the starting temperature 700 ^{o}C before the last pass the strip temperature after that pass was 615 ^{o}C.

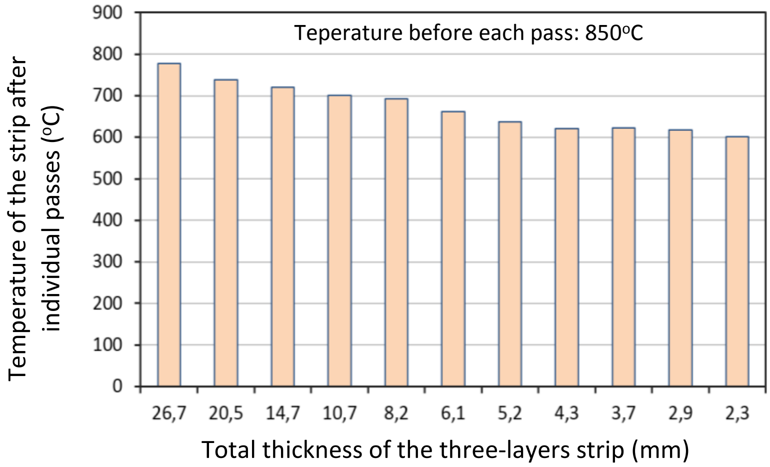

Figure 2. Decreasing of the strip temperature after corresponding pass with reducing of the total thickness of the three-layers strip.

Microstructure of the strip rolled from austenitic area (temperature 930 ^{o}C) is presented at Figure 3. Microstructure of 4.3 mm thickness strip, rolled according to the data presented in Table 2 is presented at Figure 4.

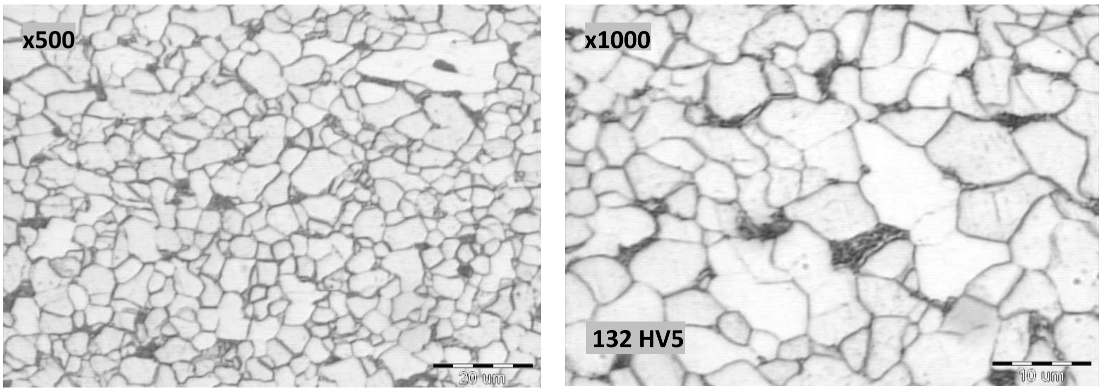

Figure 3. Microstructures of the strip rolled from 930 ^{o}C; transverse section, detail (right)

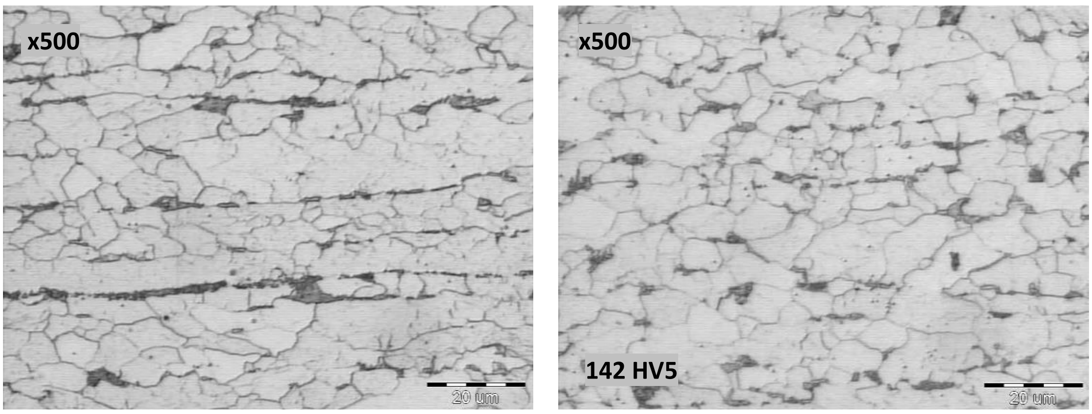

Figure 4. Microstructure of 4.3 mm thickness strip rolled in eight passes with reheating on 850 ^{o}C before each pass; longitudinal section (left), transverse section (right)

Microstructures of the strips rolled according to the rolling variants I, II and III described in Table 3 are presented at the Figures 5, 6 and 7. Corresponding microstructures of the rolled strips annealed on 700 °C for 60 minutes are presented on Figures 8, 9 and 10. Values of hardness (HV5) measurements of rolled and rolled plus heat treated strips are presented at the corresponding photos of their microstructures.

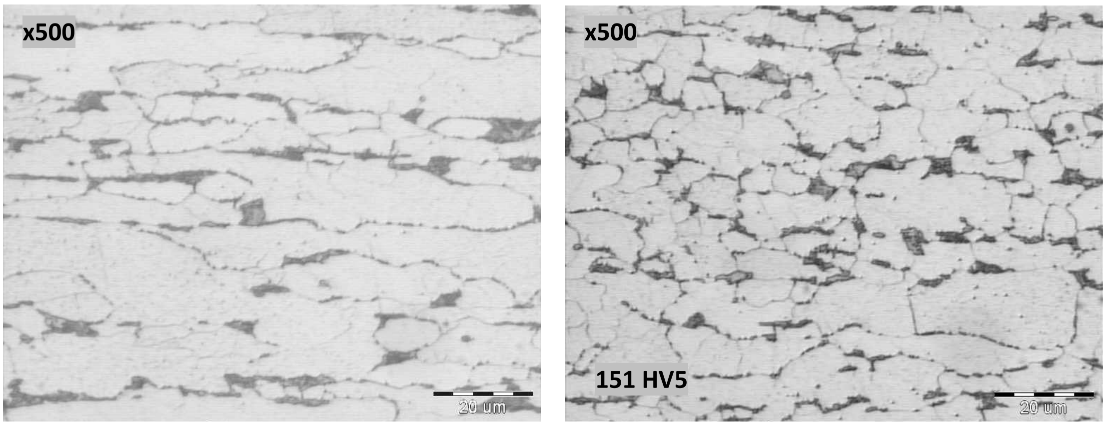

Figure 5. Rolling variant I: Microstructure of the strip rolled from 850 °C with reheating on the same temperature before each passes; longitudinal section (left), transverse section (right)

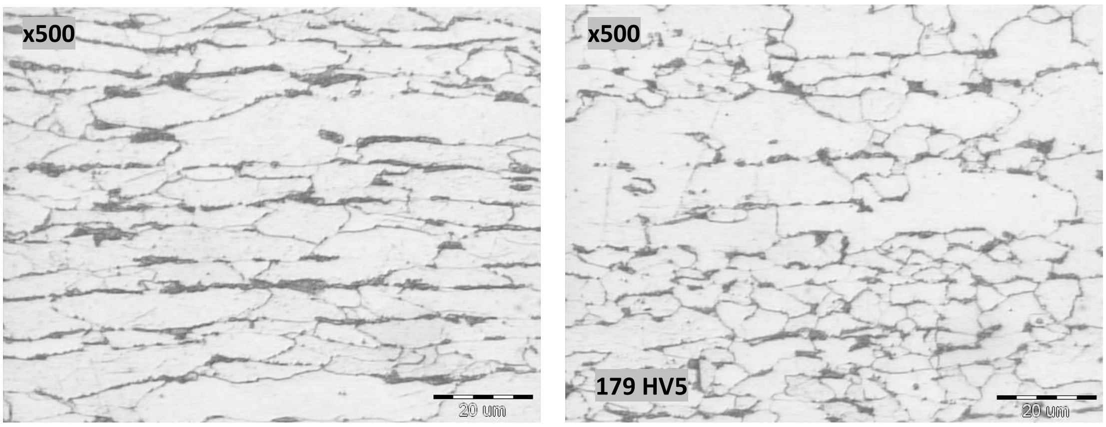

Figure 6. Rolling variant II: Microstructure of the strip rolled from 850 °C without reheating between passes; longitudinal section (left), transverse section (right)

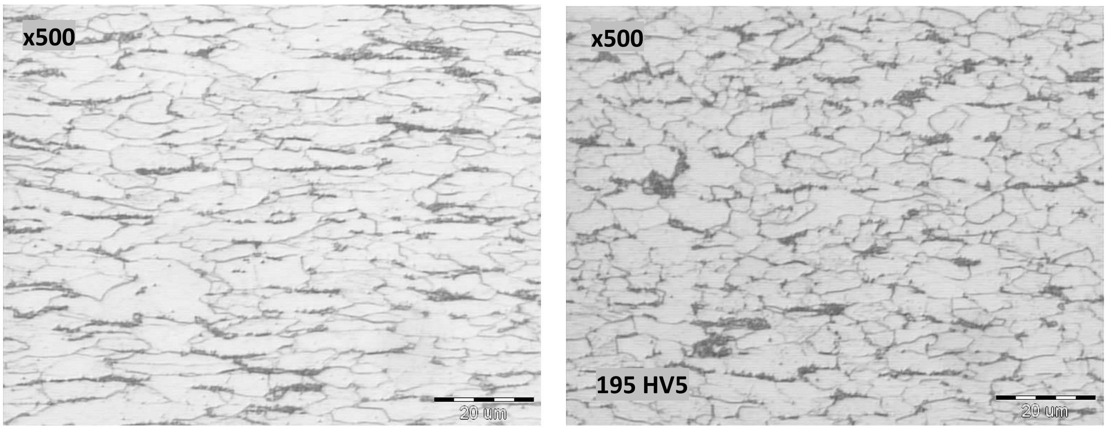

Figure 7. Rolling variant III: Microstructure of the strip rolled from 700 °C with reheating on 700 °C before the last pass; longitudinal section (left), transverse section (right)

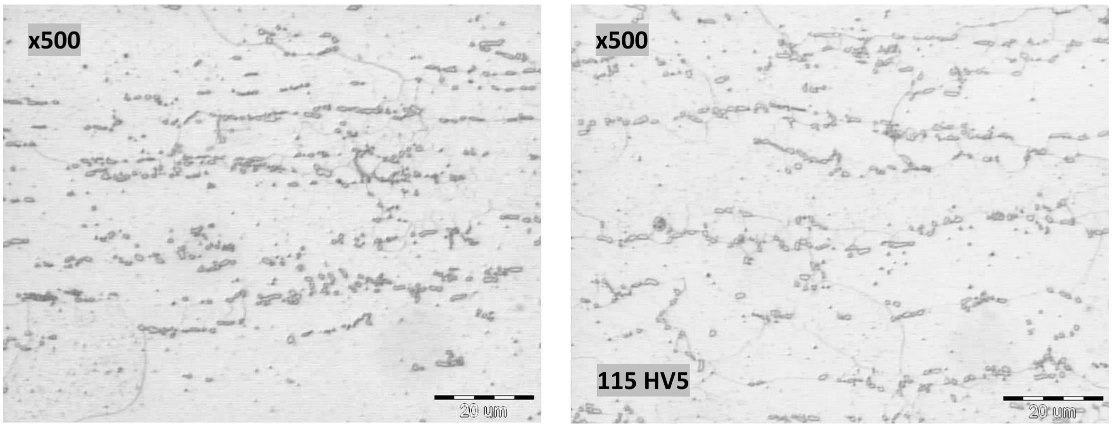

Figure 8. Microstructure of the strip rolled according to the rolling variant I and annealed at 700 ^oC/60 minutes; longitudinal section (left), transverse section (right)

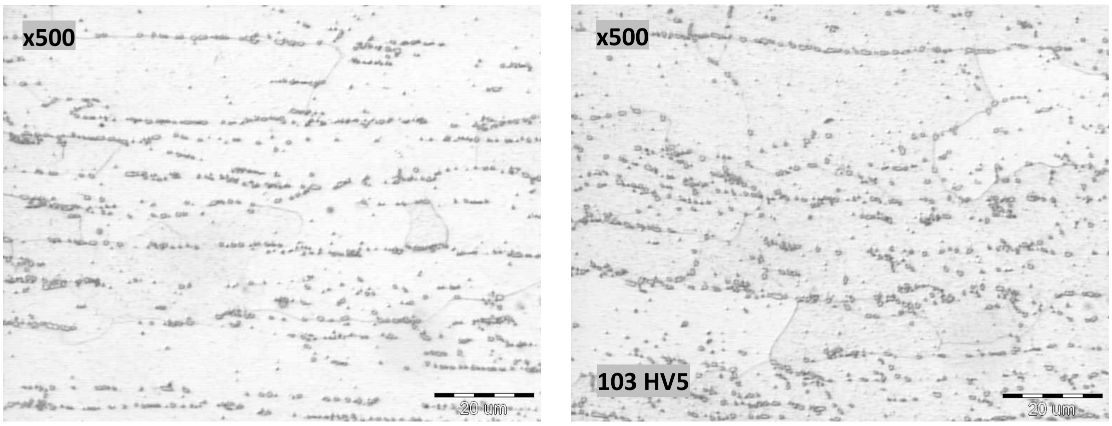

Figure 9. Microstructure of the strip rolled according to the rolling variant II and annealed at 700 ^oC/60 minutes; longitudinal section (left), transverse section (right)

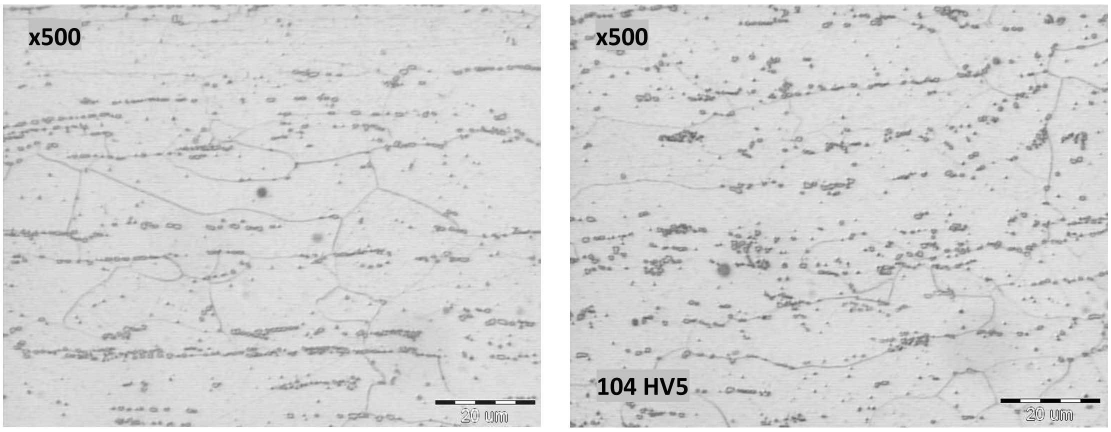

Figure 10. Microstructure of the strip rolled according to the rolling variant III and annealed at 700 ^oC/60 minutes; longitudinal section (left), transverse section (right)

4. DISCUSSION

Microstructure obtained after rolling of the strip from austenitic area (930 ^oC) is very close to the normalized microstructure since the grains are equiaxed and pearlite grains are generally compact (Figure 3). Slightly higher hardness of this strip (132 HV5) compared to the hardness of the steel DC04 in fully softened state (approximately 100 HV) is probably a result of the deformation strengthening of the strip since the rolling temperature was relatively low so the recrystallization was not completed. Rolling of the strips according to all rolling variants described in Table 3 produces the microstructure as shown at Figure 14 very similar to each other. The microstructures are consisted of elongated grains of ferrite and pearlite arranged in rows parallel to the longitudinal direction of the rolled strips.

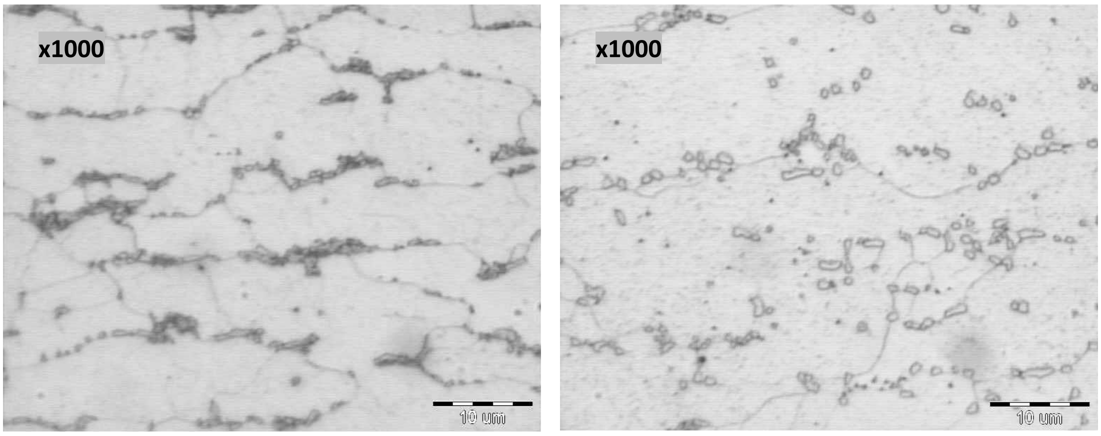

Figure 11. Microstructure of the strip rolled according to the rolling variant I before (left) and after annealing on 700 °C/60minutes (right); longitudinal sections

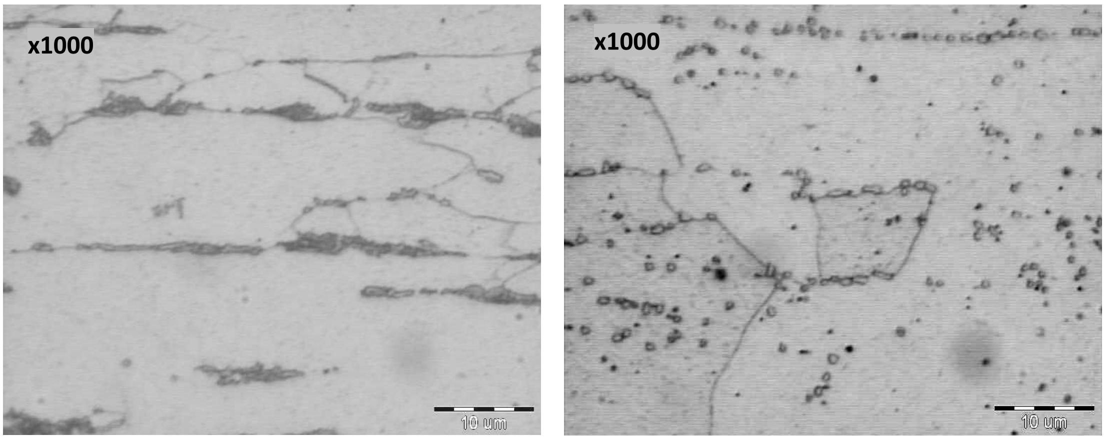

Figure 12. Microstructure of the strip rolled according to the rolling variant II before (left) and after annealing on 700 °C/60minutes (right); longitudinal sections

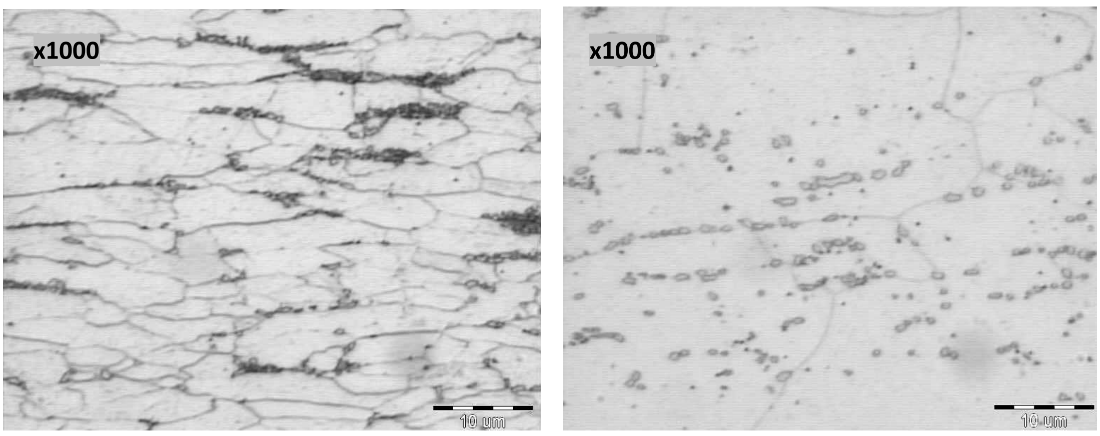

Figure 13. Microstructure of the strip rolled according to the rolling variant III before (left) and after annealing on 700 °C/60minutes (right); longitudinal sections

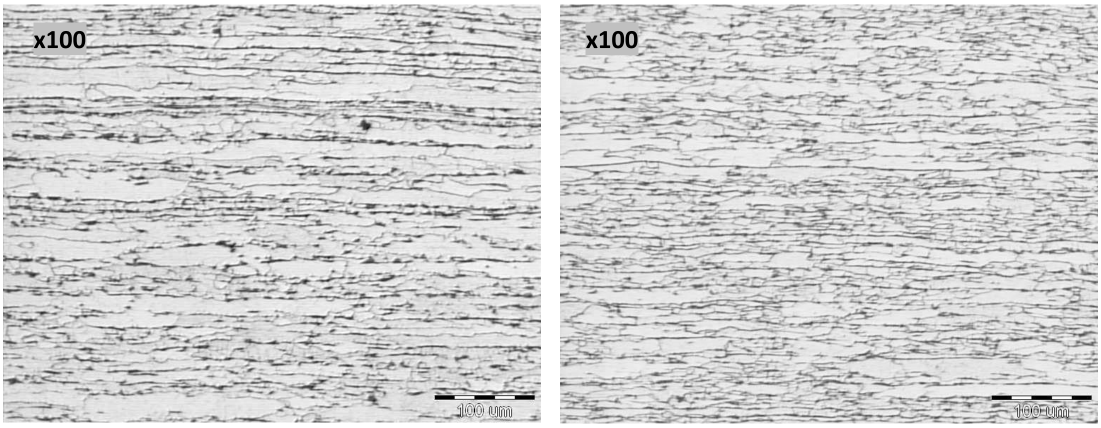

Figure 14. Microstructure of the strips rolled according the rolling variant I (left) and the rolling variant II (right); longitudinal sections

Hardness results measurements on the strips after warm rolling indicate that the highest value of the hardness was achieved according to the rolling variant III (195 HV5) the middle hardness value (179 HV5) was achieved according the rolling variant II, while the minimal hardness value (151 HV5) was achieved according to the rolling variant I. Hardness (142 HV5) of the strip 4.3mm thickness with microstructure shown at Figure 4 is very close to the hardness of the rolling variant I, because of the same thermomechanical regimes (starting temperature 850 ^{o}C and rolling with reheating on the same temperature between each of all passes). The differences in hardness occur as a result of the different starting temperatures of the rolling and different manner of the reheating. Lower starting temperature of the rolling (700 ^{o}C in variant III) gives higher hardness. Reheating between each pass on 850 ^{o}C (variant I) gives lower hardness comparing to the rolling variant without reheating on 850 ^{o}C between the last three passes (variant II). Being the microstructures and the forms of pearlite after warm rolling in the strips of all variants are very similar to each other it can be concluded that a difference in hardness is result of deformation strengthening. The deformation strengthening is eliminated by recrystallization process. Rolling on lower temperatures slow down recrystallization, so for the same percent of plastic deformation the strips rolled at lower temperatures, with one or more passes, will have higher hardness then the strips rolled at higher temperatures. Parameters of performed heat treatments are the parameters of recrystallization annealing (700 ^{o}C/60minutes). Hardness of the strips of all rolling variants was significantly reduced by the heat treatment especially in the case of variants II and III. Slightly higher hardness of the heat treated strip of the rolling variant I is a probably result of slower recrystallization because lower deformation strengthening (reheating between each pass on 850 ^{o}C). Simultaneously with ongoing of the recrystallization processes the processes of spheroidization of cement have taken place. The spheroidization of cementite is visible in microstructures of all warm rolled strips, but cementite particles are still in separated pearlite areas. On the other side after performed heat treatment the globular cementite is distributed in ferrite without evidence of presence of the original pearlite structure (Figure 5 to 13).

5. CONCLUSIONS

Regardless of the thermomechanical conditions of the warm rolling the microstructures of the rolled strips are similar to each other after the warm rolling and after the annealing. Thermomechanical cycles consisted of heating in alpha-gamma or ferrite-pearlite (700 ^{o}C), rolling, reheating on different manners to the rolling temperature and repeated rolling cause fragmentation of cementite lamellae and their partial spheroidization inside pearlite areas. Therefore, the recrystallization annealing for elimination of strain effects is simultaneously the soft annealing because of the complete spheroidization of cementite in the ferrite matrix.

Acknowledgements

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