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EFFECT OF UNEVEN PLASTIC DEFORMATION ON WIDTH OF CLAD LAYERS OF EXPLOSIVE WELDED THREE-LAYERS STRIP

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ABSTRACT
The purpose of this paper is to describe the basic reasons for obtaining narrower clad layers of CuZn10 alloy in regards to the central layer of steel strip DC04 are described. Some reasons for the reduction of the thickness of clad layers along the side edges of the strip are also described, as well as the change in the length of these parts with reduced thickness related to the reduction of the height of the rolled strip. A total spreading of the three-layers strip during hot rolling was determined and also the distance from the side edges of the strip which, after rolling, remained uncovered with the clad layers including the parts with reduced thickness of clad layers along the side edges of the strip.

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 [1] that is placed on cladding metal (flyer plate). 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 inter-atomic bonds [3]. Between two metal components an electron-shearing metallurgical bond is created [4] 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 [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 primary 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 contact sides of base metal. Since the bonded metals usually have significantly different mechanical and physical properties they will behave differently during plastic deformation. The basic reasons for obtaining narrower clad copper alloy layer in regards to the central layer of steel during and after hot and cold strip rolling are described in this paper.

In the case of hot and cold rolling of the three-layer strip (Figure 1) clad layers of CuZn10 alloy will be in contact with rolls. Because of friction on contact surface between rolls and strip, then different plasticity of clad layers and base (central) steel layer and different resistance to deformation on room and elevated temperatures of the steel DC04 and copper alloy CuZn10 during hot rolling and especially after cold rolling narrower clad layers will be obtained in regards to the central steel layer (Figure 2).

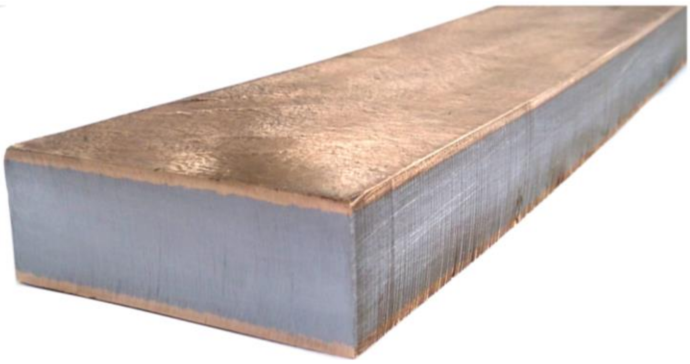

Figure 1. Sample of steel (DC04) strip with CuZn10 clad layers on both contact sides

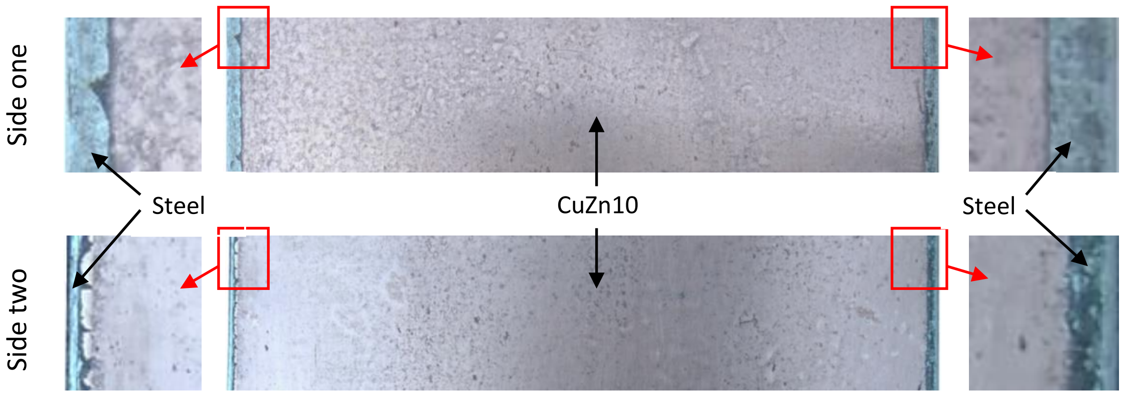

Figure 2. The appearance of both strip contact sides after the hot and cold rolling

During plastic deformation by rolling a rolled workpiece is in direct contact with the rolls in the deformation zone. Rolled workpiece is reduced in height, elongated in length and spread in width. For such changes of the workpiece form, it is necessary to achieve an appropriate sliding of the workpiece parts in the zone of deformation, all along the contact surface with the rolls. A sort of resistance originated during displacement of workpiece along the surface of the rolls is called external or contact friction. Appropriate force of resistance is called friction force. The vector of friction force is located in the contact plane between the roll and rolled strip and is directed to the side opposite to the action of the sliding [9].

External (contact) friction has a significant influence on the plastic deformation process. The effect of friction is reflected in the transition of the linear stress state, when f = 0, to the volumetric stress state when f is higher than zero in the body exposed to deformation process (f is coefficient of contact friction) [10]. Thereby the force required for deformation increases and the uneven material flow occurs.

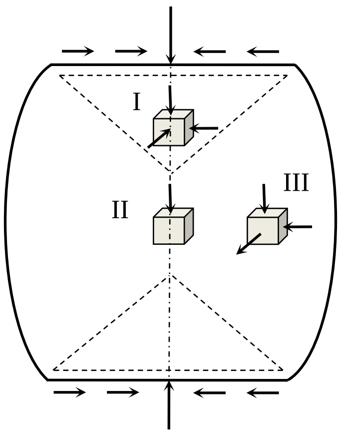

Figure 3. Friction forces and stresses during sample compression

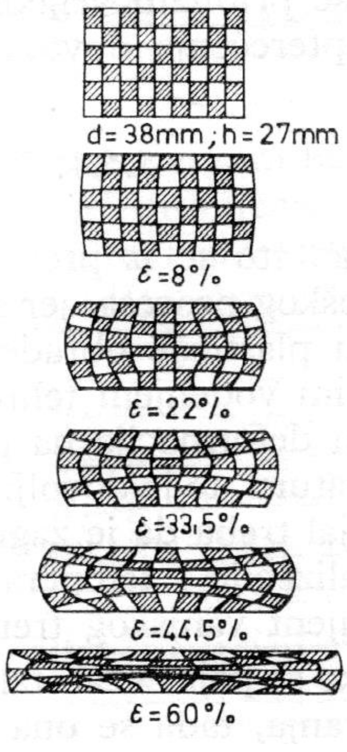

Figure 4. Uneven deformation in the compressed samples made of multicolored plasticine [10]

The uneven flow of the material in height is reflected in the fact that the friction forces acting on the contact surfaces prevent a free flow of surface layers, so they are retarded in regard to the central layers where a friction effect is smaller or none, depending on the height of the deformed workpiece (Figure 3).

Since the friction forces on the contact surfaces are oriented from the periphery to the centre, the volumetric stress state with all sides compression stresses occurs in the parts of the workpiece on the contact surfaces (zone I). If a deformed workpiece is sufficiently high, the friction force will be lost at a certain distance from the contact surface and there will be a linear stress state on compression (Zone II). Due to the fact that the workpiece is compressed, one part of the volume has to be displaced towards the peripheral parts of the workpiece, accordingly in zone III there is volumetric stress state consisted of one tensile and two compression components of stress.

Plastic deformation in zone I begins after the completed deformation in the other zones, therefore this zone is called a zone of aggravated deformation or a dead zone. This triangular zone with only small plastic deformation extends as a wedge down into the plastic zone [11]. With reduced height of the workpiece, the zone of aggravated deformation is spreading more and more through volume of the workpiece, and in the case of small workpieces it can occupy its entire volume [10]. The non-uniformity of the deformation caused by contact friction at compressed sample made of multicolored plasticine can be seen clearly at Figure 4. Maximum deformation occurs in the central part of the sample [10].

2. EXPERIMENTAL PROCEDURES

Samples for hot and cold rolling were three-layers plate obtained by explosive welding. The plates of copper alloy (CuZn10 according to the standard EN 1652) were welded to plate of low carbon steel (DC04 steel for deep drawing according to the standard EN 10130) on both contact sides. The dimensions of the three-layers plate obtained by explosive welding were 1200x2000 mm. Samples of nominal width 90 mm (Figure 1) were cut by water jet from the three-layers plate. Hot rolling was performed on the light section rolling mill SKET ϕ370 mm (8 passes) and laboratory light section rolling mill ϕ250 mm (3 passes) - Table 1.

Table 1. Data related to the hot rolling of the three-layer strips

Rolling mill	Pass number	Cross section dimensions after pass (mm)		Heating regime
		Thickness	Width	
	Staring strip	34.80 x 89.33		Heating on 850 ^{o}C
Light section rolling mill SKET ϕ370 mm	1.	26.75 x 92.66		Reheating on 850 ^{o}C
	2.	20.54 x 93.93		Reheating on 850 ^{o}C
	3.	14.73 x 96.46		Reheating on 850 ^{o}C
	4.	10.66 x 99.23		Reheating on 850 ^{o}C
	5.	8.20 x 99.66		Reheating on 850 ^{o}C
	6.	6.10 x 99.70		Reheating on 850 ^{o}C
	7.	5.21 x 99.73		Reheating on 850 ^{o}C
	8.	4.35 x 100.45		Reheating on 850 ^{o}C
Laboratory light section rolling mill ϕ250 mm	9.	3.70 x 101.00		Reheating on 850 ^{o}C
	10.	2.90 x 101.70		Reheating on 850 ^{o}C
	11.	2.33 x 102.33		-

After hot rolling and recrystallization annealing but before cold rolling an oxide film from strip surface has been removed by 7.5% sulfuric acid heated on temperature 35 – 40 ^{o}C. Holding time of the strip in sulphuric acid was 8 minute. Cold rolling of the three-layer strip was performed on the cold rolling mill LOMA from 2.33 mm on 1.33 mm of thickness. After final recrystallization annealing a newly formed oxide film has been removed on the same way as after hot rolling. At the end, an additional cold rolling was performed from 1.33 mm on 1.30 mm of thickness with the aim of preventing a localization of deformation (local plastic bending) of strip during its uncoiling [12] and to eliminate (upper and lower yield stress behaviour) yield point (skin-pass rolling) [13, 14].

3. RESULTS

To perform measurement of different dimensions of the whole strip and individual layers of the strip after any pass of hot rolling and after cold rolling the samples of 70 mm in length are cut. The results of strip height and width measurement and values of basic deformation parameters in absolute and relative amount in the height and width of hot and cold rolled strips, per pass and in the total (cumulative) amount relative to the starting dimensions of the welded strip are presented in Table 2. The results of measurement of the individual layers dimensions of the strip are presented in Table 3. Each measurement result presented in Table 3 is the mean value of three individual measurements of the thickness on different positions of sample cross-section while in the case of the width of the layers mean value of measurement on three different locations along the length of 70 mm.

Table 2. Basic deformation parameters in absolute and relative amount in the height and width of hot and cold rolled strips, per pass and in the total (cumulative) amount related to the starting dimensions of the welded strip

Pass number	Dimensions of rolled samples		Height reduction				Spreading			
	Height h (mm)	Width w (mm)	Per pass		Total (cumulative)		Per pass		Total (cumulative)	
			absol. (mm)	rel. (%)	absol. (mm)	rel. (%)	absol. (mm)	rel. (%)	absol. (mm)	rel. (%)
-	34.80	89.33	Starting workpiece							
1.	26.75	92.66	8.05	23.13	8.05	23.13	3.33	3.73	3.33	3.73
2.	20.54	93.93	6.21	23.21	14.26	40.98	1.27	1.37	4.60	5.15
3.	14.73	96.46	5.81	28.29	20.07	57.67	2.53	2.69	7.13	7.98
4.	10.66	99.23	4.07	27.63	24.14	69.37	2.77	2.87	9.90	11.08
5.	8.20	99.66	2.46	23.08	26.60	76.44	0.43	0.43	10.33	11.56
6.	6.10	99.70	2.10	25.61	28.70	82.47	0.04	0.04	10.37	11.61
7.	5.21	99.73	0.89	14.59	29.59	85.03	0.03	0.03	10.40	11.64
8.	4.35	100.45	0.86	16.51	30.45	87.50	0.72	0.72	11.12	12.45
9.	3.70	101.00	0.65	14.94	31.10	89.37	0.55	0.55	11.67	13.06
10.	2.90	101.70	0.80	21.62	31.90	91.67	0.70	0.69	12.37	13.85
11.	2.33	102.33	0.57	19.66	32.47	93.30	0.63	0.62	13.00	14.55
Cold rolling	1.33	102.33	1.00	42.92	33.47	96.18	0.00	0.00	13.00	14.55

Table 3. Dimensions of the individual layers of the strip measured on selected samples of 70mm length

Sample number	Height and width of rolled samples in mm		Thickness of the individual layers in mm			Width of individual layers measured along the samples in mm		
	Height	Width	Alloy CuZn10	Steel DC04	Alloy CuZn10	Alloy CuZn10	Steel DC04	Alloy CuZn10
1	34.80	89.33	2.990	28.887	2.923	89.33	89.33	89.33
2	26.75	92.66	2.337	22.120	2.290	92.76	93.10	92.33
3	20.54	93.93	1.810	20.600	1.733	93.10	94.76	92.70
4	14.73	96.46	1.320	12.107	1.303	94.90	97.50	94.83
5	10.66	99.23	0.967	8.813	0.883	99.00	100.13	98.40
6	8.20	99.66	0.730	6.773	0.697	98.96	100.45	98.86
7	5.21	99.73	0.450	4.320	0.443	98.26	100.86	98.16
8	2.33	102.33	0.180	1.973	0.177	99.53	102.26	98.10
9	1.33	102.33	0.098	1.138	0.094	98.40	102.30	98.26

Nine transversal samples (starting workpiece, seven hot rolled samples and one sample after cold rolling) mentioned in Tables 3 and 4 are metallographically prepared (Figure 5) to discover individual layers and to measure of their height. Also on these samples it has been measured the distance from the side edges of the strip to the place in the strip with a uniform thickness of the clad layers of CuZn10 alloy (length L_s). This L_s length includes distance from the location on the cross section from which clad layers reduce in height and length of strip part which is not covered by the CuZn10 clad (Figure 6). Results of measuring of this length on both sides are presented in Table 4.

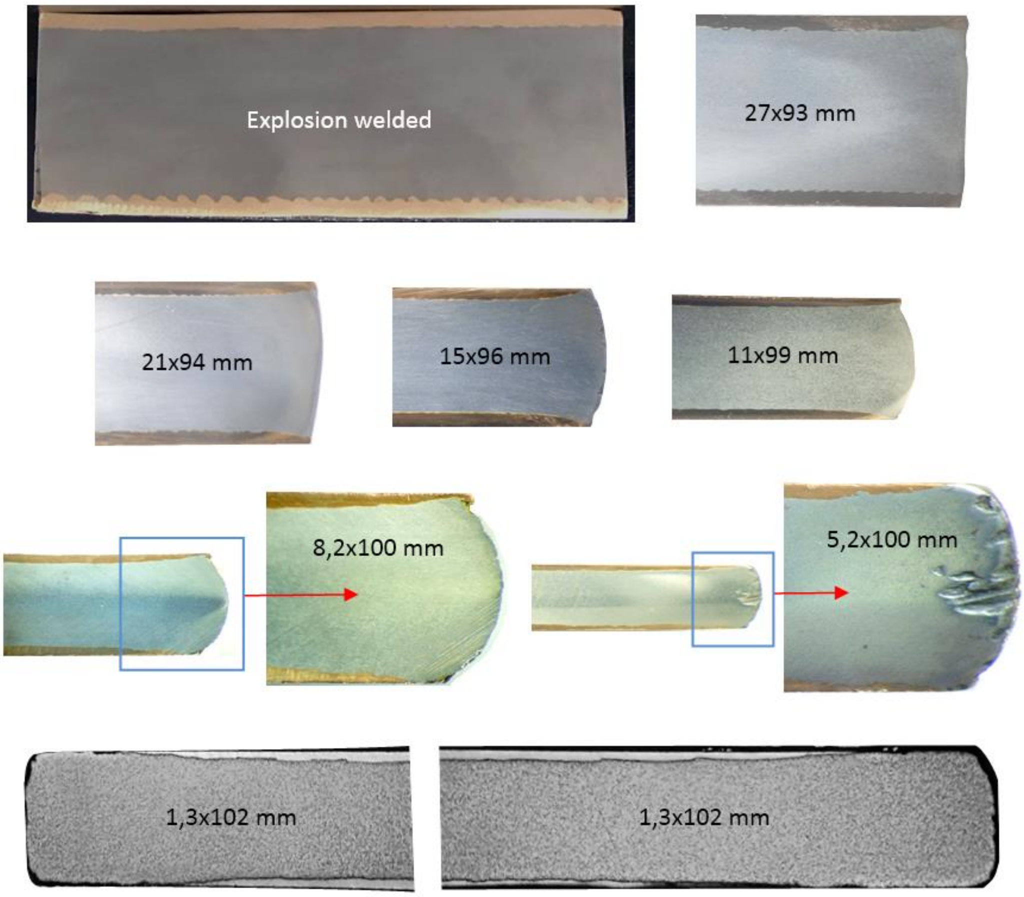

Figure 5. Cross section of the lateral edges of the selected samples

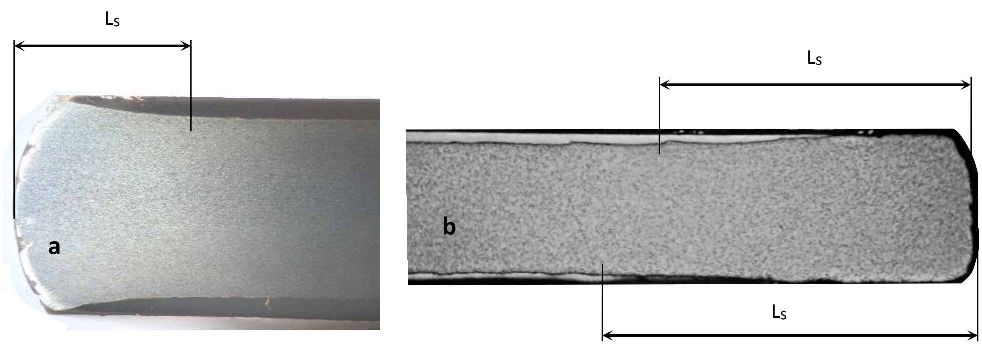

Figure 6. The method of determining the length L_s: (a) the case where there is only a reduction of clad layer height, (b) the case where L_s include and a part of the surface along the edge of the strip without this layer

Table 4. Measurement results of distance to the side edges of the strip from portion of the strip with a reduced thickness CuZn10 layer together with portion of the strip without clad layers

Dimensions of rolled samples in mm		Distances from the side edges of the strip with the complete lack of CuZn10 layer together with reduced thickness of the CuZn10 layer L_s *(mm)*					
		Upper coated layer			Lower coated layer		
Height	Width	Left side	Right side	In total	Left side	Right side	In total
26.75	92.66	4.00	5.22	9.22	4.80	3.26	8.06
20.54	93.93	8.22	5.39	13.61	3.96	6.55	10.51
14.73	96.46	9.06	8.34	17.40	8.45	8.34	16.79
10.66	99.23	7.69	8.07	15.76	7.20	5.76	12.96
8.20	99.66	6.38	5.66	12.04	6.47	4.13	10.60
5.21	99.73	5.17	3.56	8.73	4.07	4.55	8.62
2.33	102.33	4.51	3.81	8.32	4.51	3.65	8.16
1.33	102.33	2.88	3.40	6.28	2.90	2.66	5.56

4. DISCUSSION

During hot rolling of the strip with decreasing of the strip height, its width increases, so at end of the hot rolling maximum width of whole strip of 13 mm is achieved (Table 2). This spreading is spreading of the central steel layer. The width of clad layers is increased too but in smaller degree. During cold rolling generally there is no additional spreading of steel layer. Regarding the strip width of clad layers some measurement results indicates that width is reduced during hot and cold rolling but in relatively small amount (Table 3 and Figure 7). Otherwise measuring of the strip width is uncertain because of inconstant width of clad layers (Figure 2). There are three basic reasons that determine this different behaviour in terms of the width changing of the central steel layer and the clad CuZn10 layers.

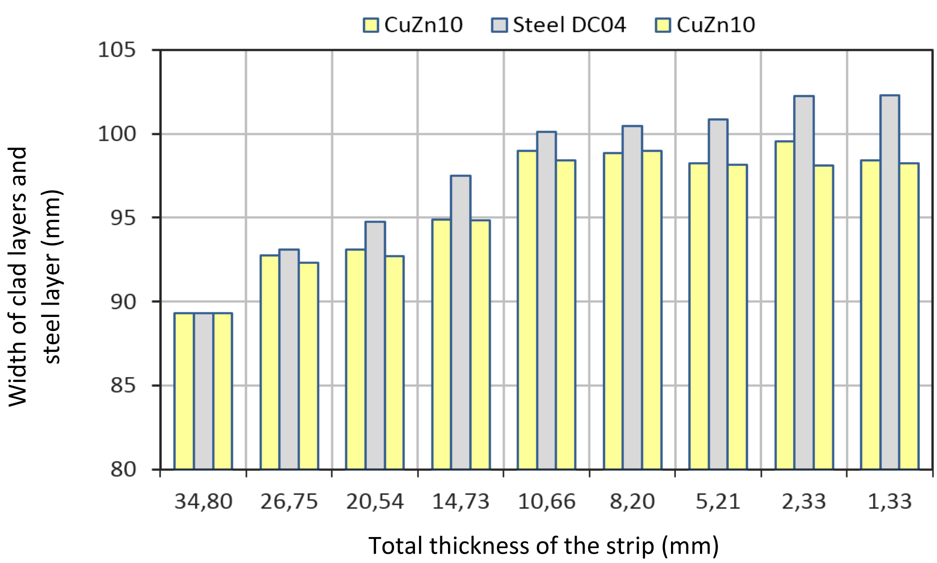

Figure 7. Changing of the width of clad layers and steel layer by reducing the total thickness of rolled strip

The most important reason is related to the uneven plastic deformation in the case of bigger reduction of the strip height. Since the clad layers are in contact with rolls the friction forces prevent their lateral flow whilst middle portion of the strip (steel layer) flows freely in that direction (barrelling effect - Figure 5 except of the starting sample and sample 27x93 mm). This happen in the case of rolling of a strip with one layer too, but in the case strip with two, three or more layers it becomes obvious.

The second reason is related to the difference in plasticity and resistance to deformation of the steel DC04 and copper alloy CuZn10. As a result of forming triangular aggravated deformation zone under contact surface between the strip and rolls which extends as a wedge down into the easy plastic deformation zone on all side edges of steel layer that are in contact with clad layers the “ridges” are formed (Figure 5 – sample 8.2x100 mm). Because of lower deformation resistance of clad layers they are forcibly spread on those “ridges”. Therefore, the width of clad layers significantly increases after reducing of the total strip thickness on 8 to 10 mm (Figure 7). With additional reducing of total strip thickness the clad layers thickness on the “ridges” becomes so small that outer parts of side edges of the clad layers are physically separated from the three-layers strip (Figure 5 – sample 5.2x100 mm).

The third reason is related to a reduction of thickness of the individual layers with the reduction of total strip thickness. Except plastic deformation carried out with the aim of achieving required strip dimensions reducing of clad layers thickness is result of two degradation processes occurred during processing of the strip. The first factor, which does not have a strong effect, is an oxidation at elevated rolling and annealing temperature (Figure 8). Another factor that has a much more pronounced influence is an action of acid when removing the oxide film after the recrystallization of the strip. Recrystallization annealing of the strip were performed after hot rolling (before cold rolling) and after finished cold rolling. As shown in Figure 8, the ratio of the sum of the thickness of the upper and lower coated layers to the overall thickness of the strip do not change significantly during the hot deformation. But this is not the case at removing of the surface oxide scale by sulfuric acid when a loss of clad thickness is bigger.

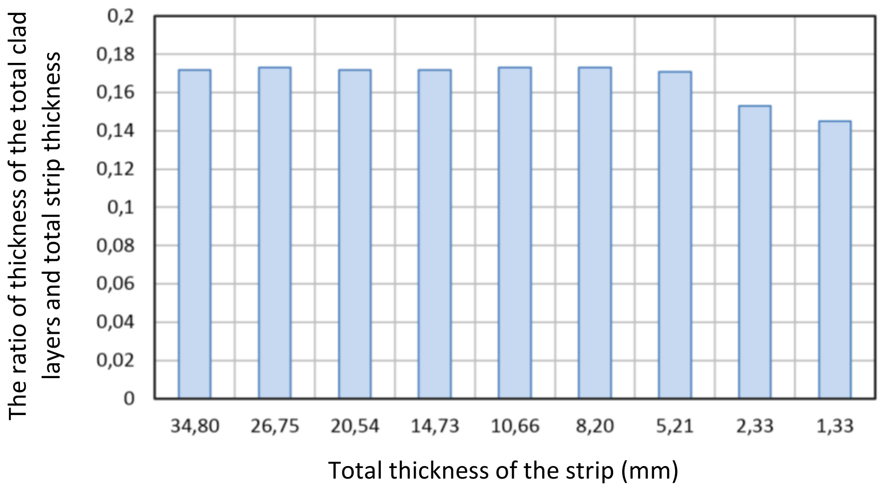

Figure 8. Diagram of the ratio of the total thickness of CuZn10 layers and the total thickness of the three-layer strip for different strips thicknesses

As a result of uneven plastic deformation, forming of dead zone, difference in plasticity and resistance to deformation of steel and CuZn10 layers and forming of “ridges” the thickness of steel layer and also clad layers is not uniform throughout the samples width. Results of measuring of the distances L_s from the side edges (barrels) of the strip to the location from which the clad layer thickness becomes uniform on both side of the rolled strip is presented in

Table 4. The same results are presented on Figure 9. The length L_s continuously increases with the decreasing of the hot rolled strip thickness while the height of the strip does not achieve values of 15 mm, after which the length L_s decreases to the end of the hot rolling (strip thickness of 2.33 mm). On thicker strips it was determined only reduction of the CuZn10 layer thickness alongside edges of the strip, while on strips with smaller thicknesses, the absence of clad layers on both faces of the strip was observed. The length L_s includes one or both imperfections alongside edges of the strip. The length L_s is significantly reduced with a reduction the strip thickness so it becomes the smallest after cold rolling. This is results of the fact that with a reduction of the strip thickness the aggravated deformation zone takes up more and more of the volume of the rolled bar. In any case, because of a necessity to produce the strips with uniform thickness of clad layer it is necessary that the width of the rolled strips is sufficiently larger than the width of the strip to be delivered after longitudinal slitting of side edges by the circular knives, at least for the length L_s.

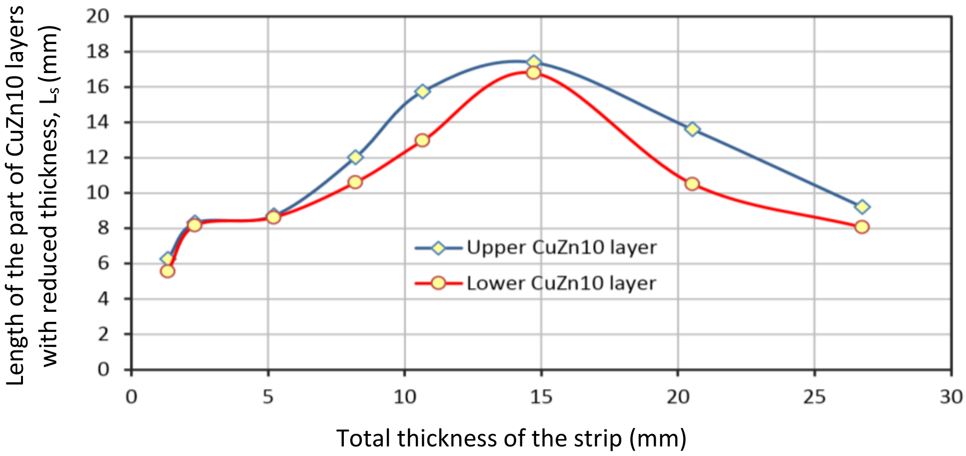

Figure 9. Dependence of the length of the clad layers part with reduced thickness (Ls) and the thickness of rolled strip

5. CONCLUSIONS

The basic reason for obtaining unequal widths of clad layers and base central steel layer is related to uneven plastic deformation which is caused by friction forces that prevent free lateral flow of surface layers contacting the rolls. Uneven plastic deformation and occurrence of the aggravated deformation zone cause forming of “ridges” alongside the edges of steel layer because of which the side edges of clad layers forcibly spread on these “ridges”. By significant thickness reducing of clad layers on these “ridges” the side edges of clad layers separate from the strip. Also forming of the aggravated deformation zone causes the occurrence of unequal thickness height of all layers throughout the samples width. Since the resistance to deformation of the clad layers (CuZn10) is lower than the resistance of central steel layer (DC04) along side edges of the strip the thickness of steel layer becomes higher while the thickness of clad layers becomes smaller. Taking into account these facts and then barrelling of the middle steel layer, general reduction of the strip thickness and the thickness of its individual layers with increasing of amount of plastic deformation and physical loss of the clad layers thickness because of elevate temperature oxidation and treatment of the strip in sulphuric acid the width of clad layers is smaller than width of the steel layer. Therefore, the width of the strip after rolling has to be bigger than width of delivering strip for L_s length to ensure uniform thickness of clad layer after longitudinal slitting of side edges of the strip by the circular knives.

Acknowledgements

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