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Residual stresses in the strips from copper-based alloys

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Materials

ABSTRACT

Purpose: The aim of this work was to define the stress state in the strips from copper-based alloys with an account of the parameters of rolling and flattening.

Design/methodology/approach: Samples of thin strips from three commercial copper-based alloys, i.e. CuSn6, CuZn33 and CuNi18Zn27, and from copper 99.98% in purity, were examined. The stress analysis was performed using X-ray diffraction method. The macro-stresses were determined by the measurements of the changes in a lattice constant and by the „$\sin^2\psi$" technique. The micro-stresses were measured by the diffraction line broadening method.

Findings: It was found that the residual stresses, measured at both surfaces of the cold rolled strip, depend strongly on the rolling conditions and on rolling gap geometry. Considerable differences between these surfaces have been observed before and after the flattening process. However, they can be significantly reduced by suitably conducted flattening process.

Research limitations/implications: Further studies are necessary to assess the possibility of reducing stresses on both surfaces of a strip in the case of non-ideal shape of rolls in a rolling mill.

Practical implications: Modification of technological flowchart for rolling strips from hardly-deformable copper-based alloys enables obtaining the required dead flatness of the strips.

Originality/value: The results from this work can be used to improve the technology of rolling and flattening thin strips from copper and copper-based alloys.

Keywords: Metallic alloys; Mechanical properties; X-ray diffraction method; Cu-based alloys; Residual stresses

1. Introduction

Most of the shape defects arising during rolling of strips is caused the appearance of internal macro- and micro-stresses in them and by diversification of these stresses over the strip thickness [1]. Even very small difference in internal stresses between the layers close to the strip surface can result in its folding, twisting or similar defects. This question is particularly important and elimination of defects is crucial when the so-called dead flatness is required from the rolled material, i.e. its strict adherence to a flat substrate under dead weight of a strip.

The correctly conducted process of rolling, with usage quality management [2] and ensuring suitable flatness and uniform thickness of the produced strip over its whole width, should take into account elastic deflection of rolls resulting from an action of roll forces appearing during rolling. These forces depend on a yield stress characteristic for the material rolled, reduction per pass, coefficient of friction between the rolls and the material rolled, rolling speed, roll radius, width of a strip rolled, tension and counter-tension forces, etc. [3, 4].

The dimensional variations leading to the appearance of deviations in flatness may be caused by non-uniformity of a crosssection of the charge, unsuitably selected roll crown for particular material and for particular rolling scheme, and by the rolling stand defects such as excessive wear of bearings. In order to ensure suitable shape of the strip rolled it is necessary to control distribution of the internal stresses behind the roll gap.

2. Material and methodology

Under this work, internal stresses in thin strips made from four types of material were investigated:

- electrolytic copper, 99.98% in purity
- tin bronze CuSn6
- two-component brass CuZn33
- high-nickel brass CuNi18Zn27.

The actual chemical composition of these materials is given in Table 1.

Table 1.
Chemical composition of the investigated alloys (in mass %)

Material	Cu	Sn	Zn	Ni	balance
Cu	99.98				0.02
CuSn6	93.30	6.33	0.21		0.16*
CuZn33	66.55		33.34		0.11
CuNi18Zn27	54.60		27.58	17.47	0.35**

* - including 0.06% P
** - including 0.21% Mn and 0.09% Fe.

They are commercial copper-based materials [5]. The CuSn6 and CuNi18Zn27 alloys belong to hardly deformable materials. Besides, the copper-tin alloys exhibit non-uniformity of its quantitative composition even after annealing, which creates additional difficulty in fabricating strips with uniform distribution of stresses [6].

The samples of strips directly after rolling and after rolling followed by strengthening by means of a straightening machine were examined. The straightening effect is accomplished in this machine due to the tensile stress produced between S-type rolls and by bending the strip several times in a three-segment roller straightener. This effect can be achieved easier in the materials, where the difference between yield point and the tensile strength is great [4]. However, it is very difficult to obtain dead flatness in thin strips in an elastic state. Therefore, the aim of this work was to develop suitable technological flowchart, including determination of the parameters of the processes of cold rolling, intermediate annealing, and straightening, so as to ensure that the obtained strips from the materials under investigation meet the criterion of dead flatness.

The main research method applied was analysis of the internal stresses performed by the X-ray diffraction method. Since it was found that the main structural component of all studied alloys was copper-based solid solution, the stresses existing in this phase were analysed on both strip surfaces using classical analytical methods [7-10]. The results from measurements of diffraction line broadening were used to determine the crystallite size and micro-stresses present in this phase.

The values of macro-stresses were determined by the measurements of a lattice constant for the (Cu) solid solution in a direction perpendicular to the strip surface, based on a position of the {111}, {002}, {022}, {113} and {222} diffraction lines and using the "$\sin^2 \Psi$" technique.

Broadening of the {111} and {222} diffraction lines has been analysed in order to determine the values of micro-stresses, whereas the "$\sin^2 \Psi$" technique was used to analyse the changes in angular position of the {113} reflection within a range of sample inclination angle from -40^0 to $+40^0$.

The analysis was performed by an incremental (stepwise) method at a measuring step of 0.01^O Θ and at the counting time of 10 s or 20 s, in dependence on the intensity of the analysed lines. It was made using Seifert-FPM XRD7 type diffractometer and the specific radiation Co Kα. In all calculations, separation of the Kα doublet was performed by the Rachinger method [11].

3. Results and discussion

The results from calculations are presented in Tables 2 - 8.

Table 2.
The changes of a lattice constant and of the values of macro-stresses in the strips from the CuNi18Zn27 alloy. Lattice constant a_o = 0.36475 nm

Cold deformation and status	Strip surface	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.	Change in $\Delta a/a$ av
0 %, hot rolled	upper	+ 82		
0 %, hot rolled	lower	- 163	- 41	
0 %, flattened	upper	- 81		
0 %, flattened	lower	0	- 40	- 1
23.5%, rolled	upper	+ 164		
23.5%, rolled	lower	- 576	- 206	
23.5%, flattened	upper	- 55		
23.5%, flattened	lower	- 274	- 165	- 41
55.7%, rolled	upper	- 88		
55.7%, rolled	lower	- 1179	- 634	
55.7%, flattened	upper	- 384		
55.7%, flattened	lower	- 685	- 535	- 99

Table 3.
Crystallite size and the values of micro-stresses in the strips from the CuNi18Zn27 alloy

Cold deformation and status	Strip surface	D nm	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.	Change in $\Delta a/a$ av
0 %, hot rolled	upper	>>200	148		
0 %, hot rolled	lower	>>200	14	81	
0 %, flattened	upper	>>200	368		
0 %, flattened	lower	>>200	341	354	+ 273
23.5%, rolled	upper	118	581		
23.5%, rolled	lower	125	579	580	
23.5%, flattened	upper	127	595		
23.5%, flattened	lower	125	584	590	+ 10
55.7%, rolled	upper	112	870		
55.7%, rolled	lower	94	814	842	
55.7%, flattened	upper	110	853		
55.7%, flattened	lower	105	838	845	+ 3

Table 4.
The changes of a lattice constant and of the values of macro-stresses in the strips from the CuSn6 alloy. a_o = 0.36498 nm

Cold deformation and status	Strip surface	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.
0 %, flattened	upper	+82	
0 %, flattened	lower	- 110	- 14
18.4%, flattened	upper	- 301	
18.4%, flattened	lower	- 247	- 274
24.5%, flattened	upper	- 740	
24.5%, flattened	lower	- 356	- 548
38.0%, flattened	upper	- 1617	
38.0%, flattened	lower	- 767	- 1192

Table 5.
Crystallite size and the values of micro-stresses in the strips from the CuSn6 alloy

Cold deformation and status	Strip surface	D nm	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.
0 %, flattened	upper	57	70	
0 %, flattened	lower	65	310	190
18.4%, flattened	upper	44	464	
18.4%, flattened	lower	67	509	487
24.5%, flattened	upper	45	607	
24.5%, flattened	lower	73	544	576
38.0%, flattened	upper	46	613	
38.0%, flattened	lower	58	740	677

Table 6.
The changes of a lattice constant and of the values of macro-stresses in the strips from the copper alloys (a_o = 0.36147 nm) and from the CuZn33 brass (a_o = 0.36941 nm)

Material and status	Strip surface	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.	Change $\Delta a/a$ av
copper, rolled	upper	- 1080		
copper, rolled	lower	- 553	- 817	
copper, flattened	upper	- 968		
copper, flattened	lower	- 774	- 871	+54
CuZn33, rolled	upper	- 432		
CuZn33, rolled	lower	- 378	- 405	
CuZn33, flattened	upper	- 325		
CuZn33, flattened	lower	- 271	- 298	- 107

Table 7.
Crystallite size and the values of micro-stresses in the strips from copper and from the CuZn33 brass

Material and status	Strip surface	D nm	$\Delta a/a_o$ 10^6	$\Delta a/a_o$ 10^6, av.	Change $\Delta a/a$ av
copper, rolled	upper	332*	103		
copper, rolled	lower	316	212	158	109
copper, flattened	upper	311	85		
copper, flattened	lower	302	106	96	21
CuZn33, rolled	upper	83	547		
CuZn33, rolled	lower	75	464	505	- 83
CuZn33, flattened	upper	80	532		
CuZn33, flattened	lower	79	528	530	- 4

* - The values of D over 200 nm (i.e. over applicability limit of the method applied) are approximate.

The results from measurements presented in Tables 2, 4 and 6 include the values of macro-stresses in the direction perpendicular to the strip surface, which are clearly comparable with each other, but no indication is given on their spatial distribution. In order to determine this distribution a sample from copper strip was examined by the "$\sin^2 \Psi$" method, which enables determination of a difference in the state of stresses on strip surfaces before and after strengthening.

Table 8.
The values of main stress tensors for a copper strip, determined before and after strengthening process, MPa

Upper surface of the strip:					
before the process			after the process		
217,4	0	0	233,9	0	0
0	-137,6	0	0	-257,3	0
0	0	-95,7	0	0	1,2
Lower surface of the strip:					
before the process			after the process		
172,2	0	0	87,2	0	0
0	-43,0	0	0	-171,1	0
0	0	-59,9	0	0	32,1

3.1. Results from analysis of lattice constant changes

The changes in a lattice constant resulting from cold deformation and the differences between the values of this constant on the top and bottom surface of the strips were analysed showing that these differences were regular and dependant on the parameters of cold deformation and on whether the straightening process was used or not.

The macro-stresses are most frequently positive (tensile) on the top surface of a strip and negative (compressive) on the bottom surface. In both cases, the lattice constants are smaller on a bottom surface. Although the differences are caused by deformation of a crystallite lattice (its spreading or compression) by only about 0.1% or less, they are sufficiently significant that may result in noticeable deviations from flatness. The process of bending strips in a straightening machine causes slight changes in the lattice constants, which leads to a decrease in a difference between the states of stress on both surfaces of the strip and to a slight reduction in an average value of these stresses.

3.2. Results from analysis of micro-stresses and of the size of crystallites

Analysis of micro-stresses and of the size of crystallites in the examined strips (in this case the crystallites are referred to as so-called mosaic blocks within the grains, free of defects and separated from other blocks by low-angle boundaries) has shown that the studied cold-rolled alloys had the crystallites about 100 nm in diameter. Smaller crystallites, of an order of 50 nm even after hot rolling, were found in the CuSn6 bronze, which was probably due to the presence of the Cu_3P phase in this alloy, which played a role of modifier. Besides, some diversification in the size of crystallites was found in this alloy, which was greater than in other materials under investigation. Large dimensions of the crystallites in a copper strip are related with small cold deformation and high metal purity. An average diameter of crystallites in the strips examined decreases slightly with cold reduction, although the differences are not significant. The straightening process does not result in noticeable changes in the diameter of crystallites.

However, considerable differences were found between the size of micro-stresses measured on both surfaces of a strip. These are mostly greater on the top surface and their magnitude increases with the increase in reduction used during cold rolling, whereas at smaller reduction the difference between micro-stresses on both surfaces is smaller. If straightening is used, then an average value of micro-stresses increases but a difference between those on both surfaces is smaller.

The comparison between lattice constant changes ($\Delta a/a_o$) caused by macro-stresses, which were determined by the lattice constant measurement method, and the values of micro-stresses determined by analysis of a change in diffraction lines profile, indicates that the values of macro-stresses are usually higher from those of micro-stresses, sometimes even by several times.

4. Conclusions

From the results obtained under this work the following conclusions can be drawn:

1. The strips under investigation exhibited macro-stresses directly after rolling, which were diversified on both surfaces of the strip. These macro-stresses were usually of a tensile character on the top surface and of compressive character on the bottom surface, or, particularly after major cold deformation, compressive on both surfaces but stronger on a bottom one. The process of their straightening, including deformation by bending, did not result in the changes of a character of stress distribution but there were smaller differences in a stress level between both strip surfaces and its value was slightly lower.
2. The micro-stresses are greater on an upper strip surface and their value increases with cold deformation, whereas their diversification between surfaces decreases with deformation. In the case of large disproportions between both strip surfaces, the straightening process reduces them.
3. Based on analysis of the results, modification of technological flowchart of rolling the strips has been proposed, including those from hardly-deformable CuSn6 and CuNi18Zn27 alloys, so as to obtain required dead flatness in them.

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