Investigation of blank bow defect after roller leveller by finite element analysis

K A Trusov¹, P A Mishnev¹, E A Garber², N L Bolobanova², D V Nushtaev³ and K V Ardatov⁴

¹ JSC «Severstal Management», 30 Mira street, Cherepovets, RU-162600, Russia
² Cherepovets State University, 5 Lunacharsky street, Cherepovets, RU-162600, Russia
³ TESIS Ltd., 18 Unnatov street, Moscow, RU-125083, Russia
⁴ Moscow Aviation Institute (National Research University), 4 Volokolamskoe shosse, Moscow, RU-125993, Russia

E-mail: ka.trusov@severstal.com

Abstract. Sheet metal often shows curvature, shape defects and internal (residual) stresses which are not complying with the increasing requirements for the quality needed for customers. Roller levelling is one of the ways to flatten a metal sheets. The setting up of such machines is extremely complex and mainly depends on the operator’s experience. The main objective of this paper is investigation of adjustable parameters of roller leveller together with elastic-plastic material behaviour on the internal stresses formation. High and unbalanced values of residual stresses lead to blank bow defects in a final product. In this study, numerical finite element (FE) 2D-model of roller levelling process is proposed to use. Properties of the material were determined experimentally. The blank bow magnitude was simulated and compared with experimental results and have a good accuracy for FE prediction.

1. Introduction
Roller levelling is complicated forming process to minimize shape defects and decrease internal (residual) stress using a leveller where cyclic alternating loads applied to the strip when material bends and moving through a two rows of rollers. Roller levelers usually used when need to eliminate common shape defects like edge wave and buckle, i.e., unevenness length in both longitudinal and transverse directions. Classical theories of leveling provide some good recommendations to flatten a sheet with these common defects [1, 2]. In modern roller leveler machines strip moving from heave penetration at the entry and gradual decrease in penetration to the end. At the end of leveler, distance between the top and the bottom rollers should be about the material thickness [1, 3]. However, when the sheet is flat after leveling remains an open question about investigations of the residual (internal) stresses [3] because in the further cutting into designed shape by plasma, water jet or laser could provide shape defects like blank bow (Figure 1).

**Figure 1.** Flat sheet after levelling (a) and blank bow after plasma cutting (b).
Several articles [1, 2, 4] provide guidelines how to determine roller leveler parameters for specific steel grades and thickness and get flat strip or sheet after leveler. Behrens [4] proposed an analytical model to calculate and eliminate edge and centre waves under the MATLAB programming environment.

Bogatov [5] made experimental investigation and mathematical simulation about stress distribution in steel specimens after one cycle bending.

Numerical simulations were used by [6-11] to experimental investigation energy-power parameters and final flatness of the sheet. Madej [6] researched material hardening laws under alternating low cyclic loading and unloading and made conclusion that combined hardening model should be used. Grüber [7] investigated leveling process with respect to the initial stress and strain distribution in the pre-levelled sheet metal but without any information about stress distribution in levelled sheets. In papers [8, 9, 10] authors study residual stresses induced by roller levelers. For example, Kaiser [10] made optimization algorithm and illustrated the influence of the roller adjustments on residual stress distribution for 9 rolls leveler and 8mm thickness steel.

A look on the afore summarized works in the field of roller levelling shows that no one estimate blank bow under residual stress distribution after levelling. In this study, numerical simulation have been carried out for roller leveler to investigate the problem of blank bow for 3mm thickness steel.

2. Model description
The 15-roller levelling process is modelled in Abaqus/Standart [12] as a 2D plane strain model. Strip is 3 mm in height, the radius of the rollers is R and the roller pitch is 1.1R (Figure 2). Linear velocity of levelling line is 1 m/s.

![Figure 2. 15-roller leveller scheme.](image)

The material law used in this model is combined kinematic-isotropic hardening [6, 12]. This hardening model take into account for the bauschinger effect. This effect is characterized by a reduced yield stress upon load reversal after plastic deformation has occurred during the initial loading.

Strain-stress curves are obtained experimentally by uniaxial static tensile test for steel grades S235MC and S355MC. Figure 3 shows an example of st curve for S355MC.

![Figure 3. Strain-Stress curve for S355MC.](image)
The rollers are modeled as analytical rigid bodies. The height of the strip is discretized by 32 plane strain elements CPE4R. Use of such elements allows to take into account the distributions of transverse stresses, weight of the strip and gravity. Width of the strip and transverse thickness is 1500 mm.

Pre-levelled strip is assumed to be in stress-free state. The contact between the rollers and the strip is modeled with Coulomb friction with the friction coefficient $\mu=0.15$.

This model is used to calculate residual stresses along sheet thickness after levelling. Figure 4 shows an example of longitudinal stress distribution. Residual stress-strain fields is transferred to next model with one-meter-long steel sheet and 3 mm thickness. Under pre-stressed state and gravity this sheet bends and estimate blank bow after cutting could be analyzed regarding various adjustments of rollers.

![Figure 4. Longitudinal (Max. In-Plane Principal) stress distribution in model, MPa.](image)

### 3. Results and discussion

In order to investigate the effect of roller leveler adjustments on residual stresses and blank bow magnitude series of simulation are carried out. Before cutting strip is moving along rollers with various adjustments that presented in Table 1, where $y_2$ is displacement for first top roller and $y_{14}$ for last roller. At the same time, the capabilities of the leveler are taken into account too – maximum difference between $y_2$ and $y_{14}$ is only 1.5 mm.

| Case No | $y_2$ | $y_{14}$ |
|---------|-------|----------|
| 1       | 1.8   | 0.3      |
| 2       | 2.1   | 0.6      |
| 3       | 2.4   | 0.9      |
| 4       | 2.7   | 1.2      |
| 5       | 1.5   | 0        |

Curvatures of obtained residual stresses along sheet thickness after levelling are shown in Fig. 5 (for S235MC) and Fig. 6 (for S355MC). Shape (centre or edge) and magnitude of blank bow under this residual stresses are shown in Table 2.
Figure 5. Stress distribution after levelling for S235MC:
(a) No 1; (b) No 2; (c) No 3; (d) No 4; (e) No 5.

As shown in Figure 5 and Table 2, the magnitude of bow minimum in case № 3 and 5 for S235. When considering curve in case No 3, could be seen the following: stresses at the top point of curve are tensile and their magnitude is about 180 MPa and at the bottom point stresses are compressive and about 180 MPa too. At the same time, at point where h=1.2 mm stresses are compressive and equals 210 MPa then stresses are changing to tensile again with magnitude 210 MPa at h=1.8 mm. By considering this distribution, it is help to make a conclusion about favorable distribution along thickness – sheet will have minimum blank bow magnitude if the residual stresses will be counterbalanced and equal in value for the line that being the axis of symmetry along thickness.

Table 2. Shape and magnitude of blank bow after cutting.

| №  | S235MC Schematic longbow | Magnitude, mm | S355MC Schematic longbow | Magnitude, mm |
|----|--------------------------|---------------|--------------------------|---------------|
| 1  |                          | 49            |                          | 31,5          |
| 2  |                          | 31            |                          | 3,9           |
| 3  |                          | 5,8           |                          | 30            |
| 4  |                          | 19            |                          | 62,5          |
| 5  |                          | 2,9           |                          | 4,5           |
For steel S355MC, with higher yield strength, could be favorable case No 2 (Figure 6) where stresses are counterbalanced along thickness.

![Stress Distribution](image)

**Figure 6.** Stress distribution after levelling for S355MC: 
(a) No 1; (b) No 2; (c) No 3; (d) No 4; (e) No 5.

To validate the results of the simulation, practical levelling tests have been carried out. For industrial testing of the levelling settings of Table 1 (cases No. 2-4) steel grade S235MC were used. Each sheet after cutting was visually inspected for deviations from flatness. The selected sheets were cut into longitudinal strips with 100 mm width by the plasma cutting machine. After that, longbow magnitude were measured for each strip. For case No. 2 the magnitude is 30 mm, case No. 3 – 4 mm and case No. 4 – 20 mm and schematic longbow remains the same. The results of comparison of the experimental and calculated data leads to the conclusion that the model provides good accuracy in predicting the deviations of the sheet after cutting.
4. Conclusions and outlook

From the results of finite element simulation, recommendations about rollers adjustments are given. These recommendations were verified by experiments and give a good agreement for central part of the strip in width. To investigate residual stresses at edge of the strip needed to take into account shape defects before leveling (e.g. edge waves) and make a 3D calculation.

It was found that magnitude of long bow and residual stresses distribution is able to be controlled by leveler settings like adjusting rollers positions. For steel grades with lower yield strength needed lower penetration at entry otherwise longbow may occur again.

In future research, the obtained data will be used to investigate how incoming flatness defects can influence the levelling result in practice. Furthermore, a multitude of simulations for different materials and conditions will be conducted to identify suitable and robust levelling strategies for roller levelling.

References

[1] Nedorezov I V 2003 Mathematical simulation of the levelling processes on multiroller machines (Ekaterinburg: AKVA-press)
[2] Chen W H, Juan L I U, Cui Z S, Wang Y J and Wang Y R 2015 Journal of Iron and Steel Research, International 22(8) 664–71.
[3] Totten G E (Ed) 2002 Handbook of residual stress and deformation of steel (USA: ASM international)
[4] Behrens B A, El Nadi T and Krimm R 2011 J. of Mater. Process. Technol. 211(6) 1060–8.
[5] Bogatov A A 2012 Proc. Int. Conf. on Innovative Technologies in Metallurgy and Machine Building (Russia: Publishing house of Ural University) 95–101
[6] Madej L, Muszka K, Perzyński K, Majta J and Pietrzyk M 2011 CIRP Annals-Manufacturing Technology 60(1) 291–4.
[7] Grüber M, Oligschläger M and Hirt G 2015 Key Engineering Materials vol 651–653 pp 1023–1028
[8] Srimani S and Basu 2003 J. Strain Anal. Eng. Des. 38 261-8.
[9] Song H, Wang P, Fu L, Chen M, Wang Z and Sun H 2011 Shock and Vibration 18 171–80.
[10] Kaiser R, Hatzenbichler T, Buchmayr B and Antretter T 2014 Materials Science Forum (Switzerland: Trans Tech Publications) vol 768 pp 456–463
[11] Grüber M, Oligschläger M and Hirt G 2014 Advanced Materials Research (Switzerland: Trans Tech Publications) vol 1018 pp 207–214
[12] Abaqus Online Documentation, Dassault Systèmes, 2017.