

Influence of selected certain force and energy parameters of modern levelling machines on the reliability of sheet metal straightening processes in roll forming and slitting lines

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Abstract

This study evaluates the reliability of an 11-roll leveler when processing high-strength steels (HSLA, DP) instead of conventional structural grades (S235JR). Key indicators: leveling force, torque, drive power, and critical roll loads, were analyzed to define safe operational zones. For DP steels ($R_e = 650$ MPa), maintaining structural integrity necessitates a 30% speed reduction and a 43% width reduction (from 1500 to 850 mm). Under these conditions, the machine operates at its technical limit, utilizing 99% of drive power and 98% of allowable force. A 23% load increase on the third roll highlights potential risks to the bearing system's fatigue life. The findings provide practical guidelines for process engineers to optimize roll forming lines, minimize residual stresses, and prevent mechanical failure. The results demonstrate that processing advanced materials on existing machines is feasible but requires radical parameter adjustments to ensure the durability of the drive transmission and roller supports.

Keywords: fatigue life, high-strength steel, structural integrity, sheet leveling, machine capacity limits, force-energy parameters

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Highlights

- Leveling of HSS grades on conventional machines is technically feasible.
- Drive power is the critical limit, reducing the safety margin to only 1,2%.
- Strip width must be reduced by 33–43% to ensure structural integrity.
- A 23% load increase on rollers threatens the fatigue life of the bearing system
- A model supports decisions on parameter reduction vs. machine upgrades.

1. Introduction

Modern structural materials are an indispensable attribute of technological development across the broadly defined industry. Whether analyzing the transport sector, including automotive, aerospace, maritime, and rail [1–3] or the architectural, catering, and even space industries, new materials are

encountered everywhere [4,5]. Most innovative materials offer not only a range of high performance characteristics, such as wear resistance, low weight, and higher thermal resistance, but in most cases, they are characterized by an increase in mechanical strength. Currently, we are not discussing strength improvements on the scale of a few or several percent. For several years, high-strength steels have been characterized by a manifold increase in strength parameters, reaching up to 1200 MPa for UHSS (Ultra High Strength Steels) compared to conventional steels [3]. The development of nanobainitic steel plates and their application in the construction of armored vehicles should also be noted [6]. This type of material development and its expansion into various industrial branches poses a significant challenge for the machinery industry, whose goal is to meet customer needs regarding the production of semi-finished products with high quality attributes. High quality of longitudinally or transversely cut edges and the absence of

shape defects are currently a priority in many sectors [7]. The quality of feedstock in mass production, which currently consists of steel in coils, represents a major challenge for teams of machine and production line designers. On one hand, machines and entire technological lines must cope with the increased mechanical properties of the input material; on the other hand, a process speed of up to 600 m/min must be maintained [8–11].

Almost all technological lines based on steel coil feedstock are currently equipped with multi-roll leveler modules. The primary task of these devices is to remove the so-called "coil memory" (the stress state resulting from the strip winding process) and to eliminate various types of shape defects resulting from imperfections in the sheet manufacturing process (Fig. 1). The sheet leveling process is complex and requires extensive engineering expertise regarding the design of the devices themselves, as well as scientific knowledge covering the phenomena occurring within the processed strip [12–15].

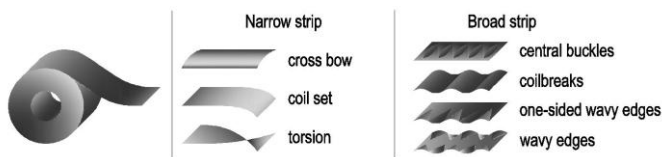


Figure 1. Coil shape defects resulting from the manufacturing process (based on [16]).

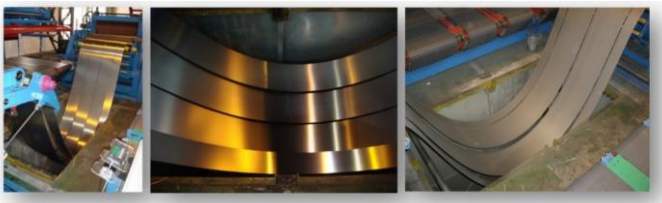


Figure 2. Non-uniform stress distribution across the strip width manifested after longitudinal slitting (source: author contribution).

A lack of a proper approach to issues related to eliminating defects in coil feedstock can significantly impact the final product quality. In certain cases, it may even lead to an inability to manufacture the intended profiles, stampings, and other components. A seemingly flat and smooth sheet surface can be the basis for erroneous decisions regarding the omission of selected processes in the production line. An example of a defect that is not visible at first glance is the latent stress state within the steel strip, which originates during the rolling process. This phenomenon is clearly manifested in longitudinal slitting

processes, particularly in the area of the looping pit. There, a seemingly defect-free strip, once slit longitudinally, results in individual strands of varying lengths (Fig. 2). Manufacturing products from feedstock with such defects can lead to a high volume of rejected parts and significant financial losses (Fig. 3).

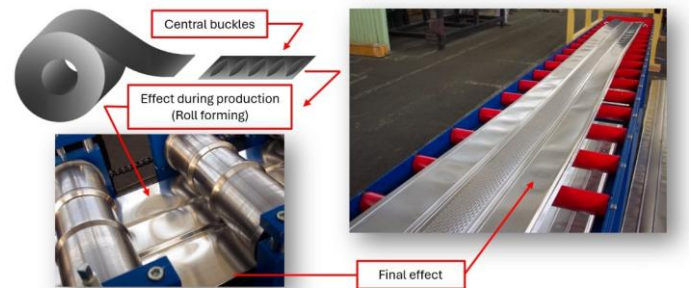


Figure 3. Potential impact of feedstock defects on the finished product (source: author contribution).

As previously mentioned, multi-roll levelers are most commonly used to eliminate shape defects in steel coils. These devices utilize a system of alternating rollers which, under appropriate pressure, power, and structural rigidity, generate the necessary elastic and plastic stress states within the processed strip. The operating principle of such systems is widely known and documented in numerous scientific papers [13–16]. Correcting simple shape defects relies on inducing a symmetrical plastic deformation within the leveled strip, covering approximately 20% of the sheet thickness. This effect is achievable by exceeding the material's yield point twofold (Fig. 4). In contrast, the correction of complex shape defects requires plastic deformation covering nearly 80% of the leveled sheet thickness (Fig. 5) [17].

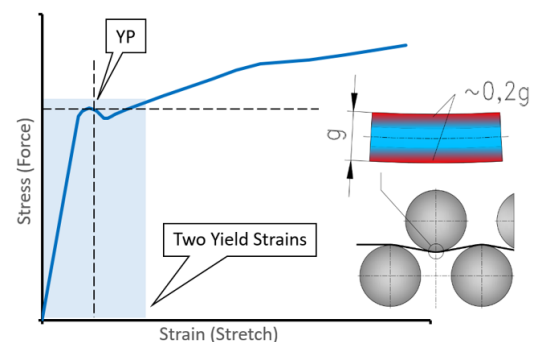


Figure 4. The rule of thumb for eliminating simple coil set is to stretch the upper and lower surfaces two yield strains, or twice the distance to the yield point. This produces permanent yielding in the outer 20 percent or so of the top and bottom surfaces of the metal (based on [17]).

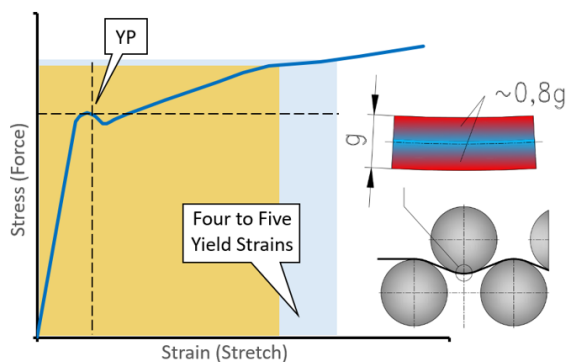


Figure 5. The rule of thumb for eliminating crossbow is to stretch the outer surfaces to four or five yield strains. To get enough crosswise elongation to eliminate crossbow, the surfaces must be elongated lengthwise three times as far. This produces permanent yielding in the outer 80 percent or so of the top and bottom surfaces with only the central core -- 20 percent -- remaining in the elastic range (based on [17]).

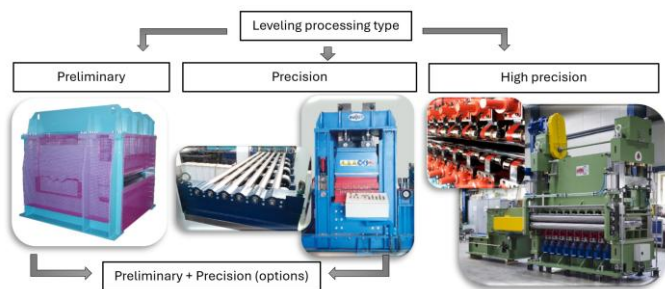


Figure 6. Basic classification of levelers based on the leveling process (source: project author and based on [14,18]).

Over recent years, the sheet leveling process, particularly machine design, control systems, and drive methods, has evolved from a simple module within a technological line into highly advanced and precision-controlled equipment. Given these facts, a systematic classification of such devices can be proposed. The primary classification is based on the type of processing: pre-leveling, precision leveling, and high-precision leveling (Fig. 6). Pre-leveling is performed on machines with a smaller number of work rolls of larger diameters. These devices represent either older design solutions or units within lines for the preliminary leveling of thick, hot-rolled plates. In such configurations, individual control of the upper cassette rolls is frequently encountered, along with the use of rolling-element bearings, facilitated by the space generated by the increased work roll diameter. For precision and high-precision leveling, machines with an increased number of small-diameter work rolls, positioned as close as possible to one another, are

utilized. Due to the limited space within the bearing arrangements, special rolling-element bearings and plain bearings with supplementary lubrication systems are employed [14].

The drive system of levelers is another design aspect where various solutions can be found, ranging from the simplest systems based on chain drives transmitting power to the work rolls of the lower cassette. Driving only the lower leveling rolls is typically found in older and more economical designs. The absence of a drive for the upper cassette rolls is usually applied in levelers integrated into technological lines, such as roll forming lines. In such cases, the risk of strip slippage within the leveler is mitigated by the strip tension generated by dozens of roll forming stands. In multipurpose standalone leveling units or precision levelers, a drive for both upper and lower cassette rolls is required. The most common solution here involves a distribution gearbox and Cardan shafts providing power to each leveling roll. An alternative is to deliver power to the upper and lower cassettes via single Cardan shafts, with the torque then distributed to subsequent leveling rolls through gears. The development of gearmotors and their precision control capabilities has led to specialized drive systems featuring direct drives, where each leveling roll in the upper and lower cassettes has its own individual gearmotor with an integrated control system. These solutions are characterized by higher energy efficiency, reduced noise levels, and a significantly simplified drive train structure (Fig. 7) [14,19–22]. Consequently, such systems lower both the operating and manufacturing costs of the equipment. The final component of modern leveler design worth mentioning is the load application system. For many years, hydraulic systems dominated this field. With the development of precision control for actuator movement at the level of tenths of a millimeter, it might seem that no further improvement was needed. However, this is not the case. Despite their advanced operating parameters, hydraulic power systems have their drawbacks. As previously mentioned, the drive system is mostly based on various solutions coupled with electric motors. Introducing an additional energy transfer medium, such as hydraulic oil, necessitates the implementation of further modules like hydraulic pumps, hoses, and valves. Increasingly, mechanical systems powered by electric motors are being used for load application. The control of these

mechanical actuators can also be performed manually. Modern screw jacks with appropriate gear ratios and precision motion control, coupled with the control system, are decisively replacing the complex and costly hydraulic systems used to date (Fig. 8).

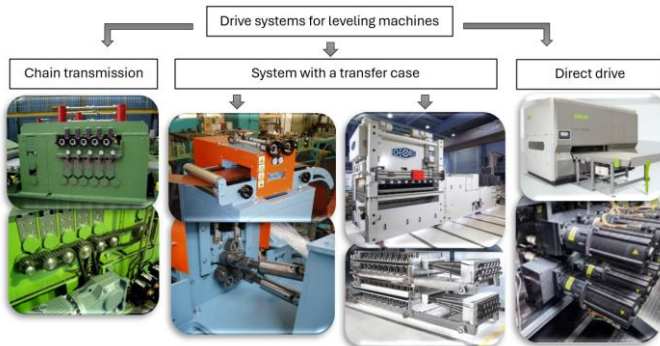


Figure 7. Drive system configurations for leveling machines (source: project author and based on [21,22]).

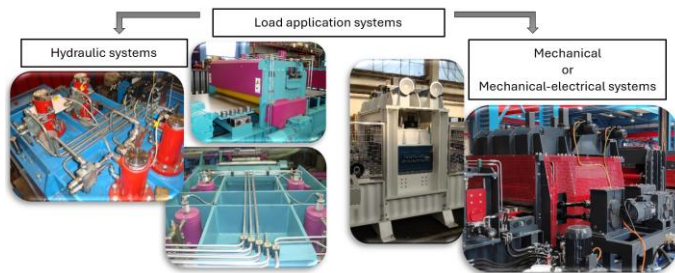


Figure 8. Load application systems in leveling machines (source: project author and based on [9]).

2. Teoretical insights

Considerations regarding the sheet leveling process must be analyzed within the context of the entire technological process of which it is a part. If the leveling process is considered on the scale of an entire production line, issues related to reliability and particularly process reliability must be addressed. The topic of process reliability, including modeling methods and related subjects, has been present in various scientific studies for many years, extending beyond the mechanical industry [23–25]. Process reliability is defined as the probability of achieving intended production goals under specified conditions and parameters for a determined period without system failure. A process can be considered reliable if, within a given timeframe, it yields a product that falls within the quality tolerance limits. Numerous components influence process reliability, the most critical being the design of the technological line, its operation, and its maintenance [26]. The design component specifically technical solutions, materials used, and

the implementation of modern machinery industry innovations ensures the capability to meet the production line's objectives. It can be assumed that in this regard, the designer's experience and their knowledge of the market, technology, and implemented processes are of paramount importance. A poorly designed production line, incorrect assumptions, or inappropriate process parameters will disqualify a given design from the production process. Regardless of other factors, such as the level of operator training, maintenance rigor, or the quality of consumables, it may turn out that process reliability is so low that the entire production process becomes uncompetitive and unprofitable. Assuming that the reliability of a process as a technological chain largely depends on the weakest link such as the leveling, roll forming, or perforating module it must be stated that no module of the technological line can be overlooked or neglected. The situation is analogous when analyzing a series system in terms of mechanical arrangements, where the reliability of the entire production line R_{PL} is the product of the reliability components of the individual line modules R_{1-N} [27].

$$R_{PL} = R_1 \cdot R_2 \cdot R_3 \cdot \dots \cdot R_N \quad (1)$$

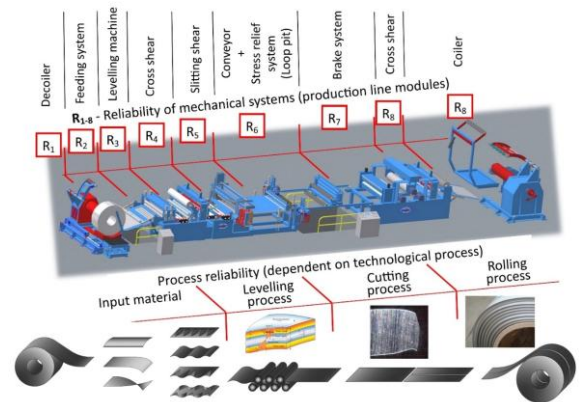


Figure 9. Mechanical reliability of a series system of constituent modules and process reliability in relation to an exemplary sheet slitting line (source: project author and based on [7,12,14,16,27,28]).

It should be noted that in the case of series systems, which most sheet metal processing lines are (Fig. 9) such as slitting lines, roll forming lines, etc. not only does the failure of one of the constituent modules cause a production halt, but the failure to meet the required quality parameters after a given process must also be treated as a failure. The specialization of the designers within the team developing a given production line is crucial and indispensable from the standpoint of overall process

reliability. The ability of experienced designers to develop subsequent modules of a production line determines its quality and suitability for the manufacturing process. The production capabilities of a technological line must always be complemented by well-trained personnel operating the equipment. In the case of leveler operation, it is essential to understand the process and accept the seemingly irrational principle that to fix sheet defects, one must work with the part of the strip that does not possess those defects [29].

2.1. Methods for analyzing the sheet leveling process

In the field of model analysis for the multi-roll leveling process, several mathematical models are available [30–32]. The objective of most analyses is to determine the required force and energy parameters of the process in relation to the geometry and mechanical properties of the leveled strip. From a machine design perspective, the most critical parameters are the required clamping force, the drive power, and the required torque. It should be noted that the total values of these parameters influence the selection of key design solutions, such as the load application system or the gearmotor specifications in the drive train. The sheet deformation process during multi-roll leveling can be compared to a sine wave with decaying amplitude. This phenomenon generates a varying distribution of forces and moments across individual leveling rolls. The highest loads are generated within the area of the first four leveling rolls. Analyzing the distribution of forces in the system is crucial in this case for the selection of the bearing arrangement and power transmission. Averaging the aggregate parameters can lead to overloads and damage in the most heavily stressed areas. Computer simulations are a significant aid in the process of selecting force and energy parameters. They facilitate the verification of assumed design solutions. One of the software packages used in the analysis of sheet leveling and roll forming processes is COPRA RF. Originally dedicated to roll forming analysis, its extensive FEM module makes it perfectly suited for verifying assumptions in the sheet leveling process [33]. As previously mentioned, the condition of plastic deformation in leveler design is a necessary requirement for ensuring process reliability. To achieve permanent changes in the material, one must operate within the plastic deformation range, rather than the elastic range, which causes only temporary strip

deformation. The practical leveling range for roll levelers is shown in Fig. 10. Within the marked area, and particularly at its end where $\varepsilon_R = 0,03$, it is necessary to verify the minimum bending radius r_{min} and the intermesh of the leveling rolls z_{max} , which must satisfy the following conditions [34].

$$r_{min} = \frac{D}{2} + \frac{g}{2} \text{ [mm]} \leq r_{req} \quad (2)$$

$$z_{max} = D + g - \sqrt{(D + g)^2 - t^2} \text{ [mm]} \geq z_{req} \quad (3)$$

where:

t - roller pitch

D - leveling roll diameter

g - thickness of the leveled strip (sheet)

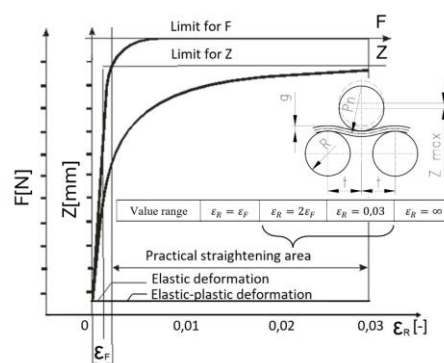


Figure 10. Practical leveling range in roller levelers [34].

The extended procedure for verifying the minimum bending radius and the roll intermesh conditions is based on a computational algorithm using the formulas presented in Table 1.

Over the years, a number of mathematical models have been developed to estimate the key power and force parameters of machines intended for sheet metal leveling. These models are based on the general principles of solid mechanics, accounting for phenomena such as elasticity, plasticity, and friction, while introducing certain simplifications necessary for the practical application of calculations in the design process. It is worth noting that the differences between the results obtained from individual calculation methods are usually minor, making them a useful tool for supporting the designer's work. The obtained values serve as a basis for selecting the appropriate drive, gearbox, bearing system, and the mechanism responsible for generating the leveling force in the roll assembly. Tables 2 and 3 summarize the formulas used to determine the main power and force parameters in multi-roll levelers. The presented algorithm considers a wide range of geometric and technological variables, allowing for its adaptation to various

machine configurations [30]. Figure 11 illustrates the operating diagram of the leveler and the notation system for the forces

Table 1. Summary of parameters required to determine correct bending conditions in roller levelers [34].

Parameter	Symbol	Value range			
		$\varepsilon_R = \varepsilon_F$	$\varepsilon_R = 2\varepsilon_F$	$\varepsilon_R = 0,03$	$\varepsilon_R = \infty$
Required bending radius	r_{req} [mm]	$\frac{g}{2\varepsilon_R}$	$\frac{g}{2\varepsilon_R}$	$\frac{g}{2\varepsilon_R}$	$\frac{g}{2\varepsilon_R}$
Required roll intermesh	z_{req} [mm]	$\frac{t^2 \cdot Re}{3gE}$	$2 \left[\frac{Ft^2}{48EJ} + C_3 \frac{t}{2} + C_4 \right]$	$2 \left[\frac{Ft^2}{48EJ} + C_3 \frac{t}{2} + C_4 \right]$	$2 \left[\frac{Ft^2}{48EJ} + C_3 \frac{t}{2} + C_4 \right]$
Bending force	F [N]	$\frac{2bg^2Re}{3t}$	$\frac{1}{t} bg^2Re \left[1 - \frac{1}{3} \left(\frac{\varepsilon_F}{\varepsilon_R} \right)^2 \right]$	$\frac{1}{t} bg^2Re \left[1 - \frac{1}{3} (0,03)^2 \right]$	$\frac{bg^2Re}{t}$
Variable	X_1 [mm]	-	$\frac{t}{2} - \frac{bg^2Re}{3F}$	$\frac{t}{2} - \frac{bg^2Re}{3F}$	$\frac{t}{2} - \frac{bg^2Re}{3F}$
Variable	α [mm]	-	$\frac{bg^2Re}{2F} - \frac{t}{2}$	$\frac{bg^2Re}{2F} - \frac{t}{2}$	$\frac{bg^2Re}{2F} - \frac{t}{2}$
Variable	$\beta \left[\frac{1}{\sqrt{mm}} \right]$	-	$\sqrt{\frac{2bRe}{3F}}$	$\sqrt{\frac{2bRe}{3F}}$	$\sqrt{\frac{2bRe}{3F}}$
Second moment of area	J [mm ⁴]	-	$\frac{bg^2}{12}$	$\frac{bg^2}{12}$	$\frac{bg^2}{12}$
Variable	C_3 [-]	-	$\frac{F}{2EJ} \left[\frac{1}{2} x_1^2 - \frac{1}{2} x_1 \right] - 2\beta\varepsilon_F$	$\frac{F}{2EJ} \left[\frac{1}{2} x_1^2 - \frac{1}{2} x_1 \right] - 2\beta\varepsilon_F$	$\frac{F}{2EJ} \left[\frac{1}{2} x_1^2 - \frac{1}{2} x_1 \right] - 2\beta\varepsilon_F$
Variable	C_4 [mm]	-	$-C_3 x_1 + \frac{F}{2EJ} \left[\frac{1}{6} x_1^3 - \frac{t}{4} x_1^2 \right] - \beta\varepsilon_F \left[\frac{4}{3} \sqrt{\alpha_1^3} + 2\sqrt{\alpha_1} x_1 - \frac{4}{3} \sqrt{(\alpha_1 + x_1)^3} \right]$		

where: $\varepsilon_F = \frac{R_e}{E}$; b - Width of the material; Re - Yield strength; E - Young's modulus

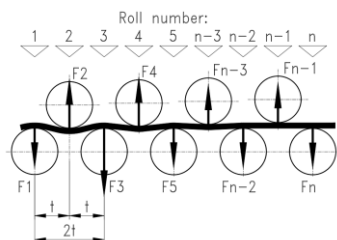


Figure 11. Schematic and notation of forces in the sheet metal leveling process.

Table 2. Summary of component variables required to determine power and force parameters in roller levelers [30].

	Symbol	Formula	Unit
Torques of individual rollers	$M_1 = M_n$	0	Nm
	$M_2 = M_3 = M_4$	ReW_p	Nm
	$M_5 = \dots = M_{n-1}$	ReW	Nm
	F_1	$\frac{ReW_p}{t}$	N
Pressure forces on individual rollers	F_2	$\frac{3}{t} ReW_p$	N
	F_3	$\frac{4}{t} ReW_p$	N
	F_4	$\frac{Re(W + 3W_p)}{t}$	N
	F_5	$\frac{Re(3W + W_p)}{t}$	N
	$F_6 = F_7 = F_{n-2}$	$\frac{4}{t} ReW_p$	N
	F_{n-1}	$\frac{3}{t} ReW_p$	N
	F_n	$\frac{ReW_p}{t}$	N

where: W - Elastic section modulus; Wp - Plastic section modulus

acting within the roll assembly.

Table 3. Summary of main power and force parameters in roller levelers [30].

	Symbol	Formula	Unit
Total force exerted by the sheet on all rollers	F	$\sum_{i=1}^{i=n} F_i$	N
Total torque required for sheet leveling	M_w	$\frac{3 Re^2 D}{4 E} [S + \frac{W}{9} (n - 5)]$	Nm
Torque loss due to friction and strip slippage	M_{t1}	$q \sum_{i=1}^{i=n} F_i$	Nm
Torque loss due to bearing friction	M_{t2}	$f \frac{d}{2} \sum_{i=1}^{i=n} F_i$	Nm
Total torque acting on the rollers	M	$M_w + M_{t1} + M_{t2}$	Nm
Motor power required during leveling	P	$M \frac{M2v}{D\eta 1000}$	kW

where:

- f – friction coefficient (dependent on the bearing system),
- d – journal diameter of the leveling roll bearing,
- v – leveling speed of the strip,
- η – efficiency of the drive transmission system,
- q – friction arm,
- S – cross-sectional area of the leveled strip.

2.2. Modeling assumptions

The modeling assumptions for the presented calculation system were developed based on real inquiries from customers in the steel industry involved in the processing and packaging of steel products such as sheets, blanks, and strips from coil feedstock. Longitudinal and transverse slitting of coiled sheets takes place on processing lines dedicated to handling feedstock with predefined parameters. Geometrically, for each slitting line, the coil feedstock has a defined width, inner and outer diameter, and, very often, mass. For technological reasons, the primary constraint for processing a given feedstock is typically the mechanical strength of the strip, which is reflected in the steel grades being processed. With the growing market demand for feedstock with enhanced strength properties, a frequent question from customers is whether a processing line purchased over a decade ago can handle materials with higher strength parameters. Most structures, drives, and other systems possess a certain safety margin, allowing them to meet contemporary requirements. Every professional slitting line is equipped with

a leveler. In most cases, this system is used to eliminate "coil set" (coil memory), but in more advanced lines, it also serves to correct various types of strip defects. The subject of this analysis is an existing leveler integrated into a sheet slitting and roll-forming line. The parameters of the leveling system are presented in Table 4. The objective of the analysis was to determine the feasibility of operating with feedstock of higher strength parameters (Table 5).

Table 4. Basic characteristics of the analyzed leveler.

Parameter	Value / Specification
Number of leveling rollers	11 (5 upper rolls + 6 lower rolls)
Diameter of leveling rollers	95 mm
Roller pitch	63 mm
Leveling roll material	42CrMo4 (heat-treated and chrome-plated rolls)
Drive power	16,5 kW
Drive torque	980 Nm
Loading system	4 hydraulic cylinders
Total applied load	564 kN
Control type	Hydraulically lowered upper cassette + individual adjustment of upper rolls
Leveling strip width range	200 ÷ 1500 mm
Leveling strip thickness	3,0 mm
Line process speed	50 m/min

Table 5. Characteristics of primary raw material and material for verification analysis.

Parameter	Core parameter group (current state)	HSLA material parameter group (Research area 1)	DP material parameter group (Research area 2)
Material group (grades to be processed)	S235JR DX51D DX52D DX53D	H220LAD, H260LAD, H300LAD, H340LAD, H380LAD, H400LAD	DP600, DP800
Design value R_e	300 [MPa]	520 [MPa]	650 [MPa]
Design value R_m	520 [MPa]	620 [MPa]	960 [MPa]
Leveling strip thickness	3,0 [mm]	3 [mm]	3 [mm]
Max. leveling strip width	1500 [mm]	?	?
Process speed	50 [m/min]	?	?

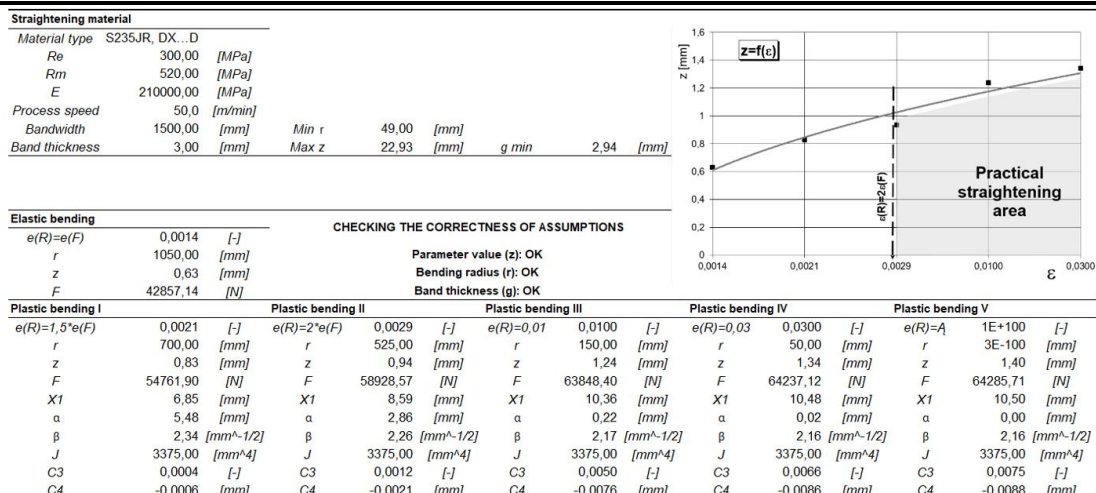


Figure 12. Verification of geometric correctness and the practical strip leveling area for the assumed criteria and the analyzed leveler (current state).

3. Calculation and modeling results

According to the adopted methodology, the fundamental step is the verification of geometric conditions. Using formulas (2) and

(3), as well as the dependencies included in Table 1, the correctness of the leveling process for the assumed criteria was verified. Detailed data for the analyzed value ranges are

summarized in tabular and graphical form in Fig. 12. Similarly, for research areas No. 1 and 2, covering material groups with increased strength parameters, such as HSLA and DP types the summaries of the obtained values are presented in Fig. 13 and Figure 14. In each case, to meet the requirements for leveling

process correctness and force-energy parameters, the strip width and process speed were adjusted accordingly. The force-energy parameters for the analyzed conditions are summarized and presented in Table 6.

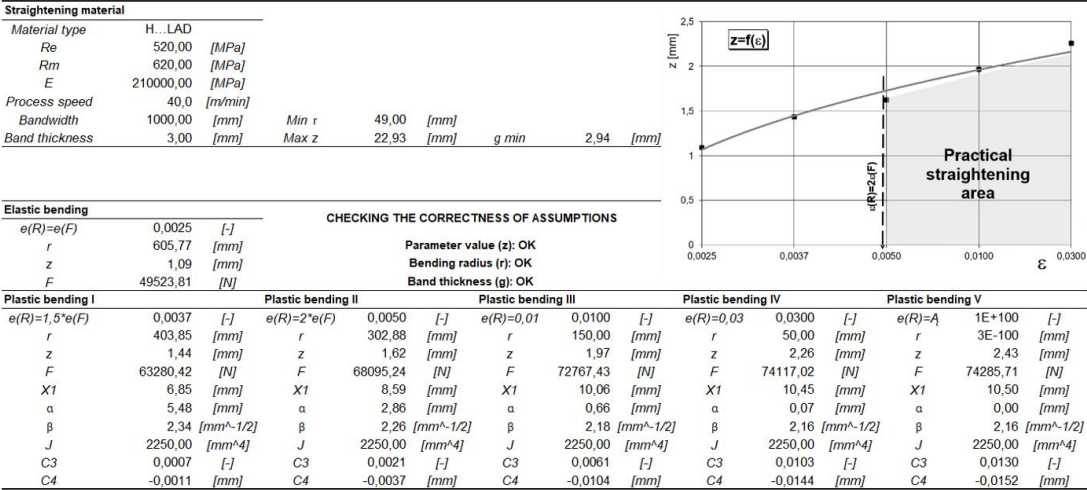


Figure 13. Verification of geometric correctness and the practical strip leveling area for HSLA material group (Research Area No. 1).

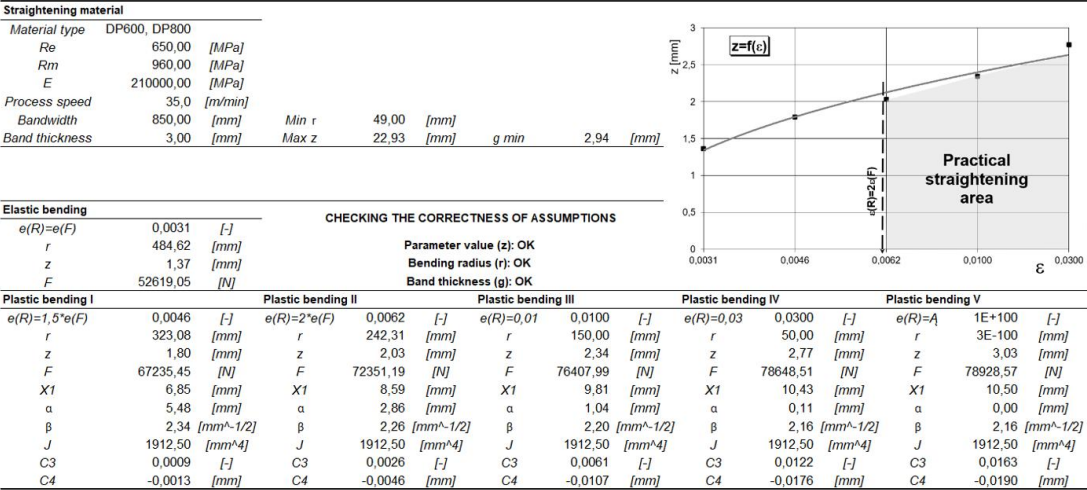


Figure 14. Verification of geometric correctness and the practical strip leveling area for DP material group (Research Area No. 2).
Table 6. Summary of force-energy parameters with unit conversion for selected analysis areas of materials subjected to the leveling process.

Core parameter group (current state)			HSLA material parameter group (Research area 1)		DP material parameter group (Research area 2)		
Roll number	F [N]	M [Nm]	F [N]	M [Nm]	F [N]	M [Nm]	
	1	16070,36	0,00	18570,20	0,00	19730,83	0,00
	2	48211,09	99,29	55710,59	114,73	59192,50	121,90
	3	64281,45	99,29	74280,79	114,73	78923,34	121,90
	4	58924,67	99,29	68090,72	114,73	72346,39	121,90
	5	48211,09	66,19	55710,59	76,49	59192,50	81,27
	6	42854,30	66,19	49520,53	76,49	52615,56	81,27
	7	42854,30	66,19	49520,53	76,49	52615,56	81,27
	8	42854,30	66,19	49520,53	76,49	52615,56	81,27
	9	42854,30	66,19	49520,53	76,49	52615,56	81,27
	10	32140,73	66,19	37140,40	76,49	39461,67	81,27
	11	10713,58	0,00	12380,13	0,00	13153,89	0,00
Total value	449970,17	695,01	519965,54	803,13	552463,36	853,32	
Required drive power	14,90 [kW]		16,19 [kW]		16,35 [kW]		

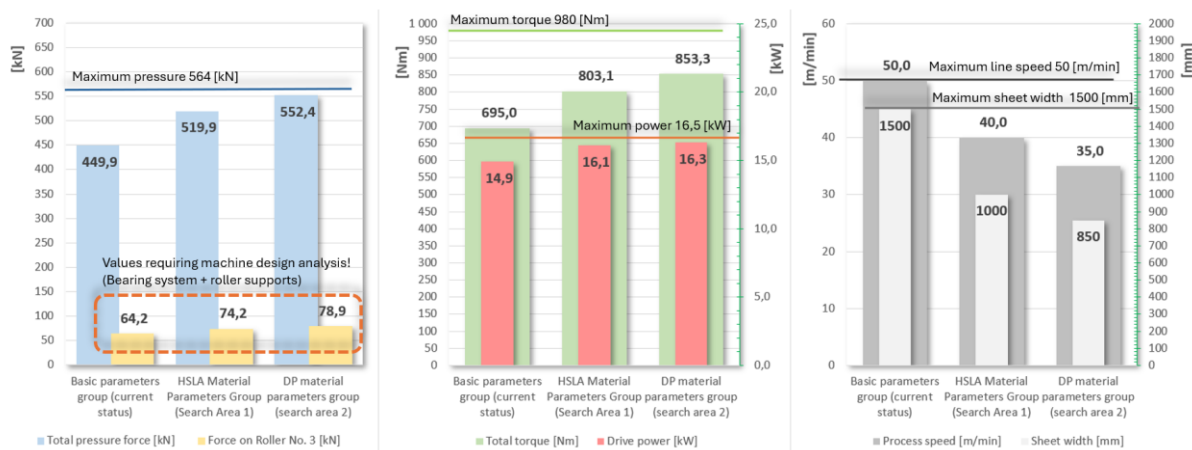


Figure 15. Comparison of selected parameters for the analyzed areas.

During the results analysis, it must be noted that we are not designing a new machine, but rather verifying the suitability of an existing leveler already integrated into the production line. In such cases, the non-exceedable constraints include parameters such as the pressure generated by the force-loading system and the drive power. Regarding the former, it is known that increasing the strength parameters of the leveled strip necessitates a reduction in its width. When operating with the permissible width for "new steel grades," the non-exceedable capacity limit of the pressure-loading system must be taken into account. This procedure also ensures that the structure, bearing system, and drive transmission units which are already adapted for such loads will not be overloaded. The second constraint for existing solutions is the installed drive power. This parameter largely determines the maximum process speed. By reducing the leveling speed for the "new steel grade," the machine can be operated without interfering with the existing drive system. Fig. 15 presents the key parameters calculated for the adopted research areas in relation to the design parameters for which the analyzed device was originally engineered. The drive power supply and control system, operated via a frequency inverter, also enables a preliminary verification of the actual power output against the results obtained from mathematical modeling (table. 7). However, it should be noted that this type of validation under industrial conditions is inherently affected by numerous external processing variables. The leveling machine's drive system is an element of a continuous production line, highly integrated with other line modules (feeding mechanisms, guiding units, the roll forming mill, and slitting shears).

Contrary to initial assumptions, these adjacent systems do not always assist the strip movement; additional tension generated, for instance, by the roll forming stations can induce longitudinal strip tension and increase vertical roll pressure, thereby elevating friction resistance on the leveling rolls. The tribological condition of the sheet metal surface (e.g., the presence of residual lubricants, rust preventatives, or technological fluids) is also of significant importance. In this study, the model validation was based on a conservative approach, incorporating the upper boundaries of normative strength parameters for the evaluated material groups, which establishes a technological safety factor. Industrial measurements were conducted for two representative sheet steel grades, whose actual strength properties (although fully compliant with metallurgical standards) were closer to nominal values, hence lower than the peak assumptions of the theoretical model. Consequently, an additional, real safety margin on the drive side was demonstrated. Due to its dynamic complexity, this phenomenon constitutes a compelling direction for further, extended industrial research.

Table 7. Validation of calculated power against industrially measured power for selected materials.

Material	Width [mm]	Speed [m/min]	Calculate [kW]	Measure [kW]	Difference [%]
S235JR /	1500	50	14,90	14,0	- 6,04
H400LAD	1000	40	16,19	15,8	- 2,40

4. Conclusion

Based on the calculations performed using the proposed mathematical models, the following conclusions can be drawn for the selected research areas:

- 1) Increase in mechanical loads along with yield strength: The analysis shows a direct correlation between the increase in material yield strength (R_e increasing from 300 MPa for structural steels to 650 MPa for DP steels) and the generated clamping forces and torque, which necessitates a radical change in the machine's operating parameters.
- 2) Utilization of maximum clamping force: The total clamping force for DP material group reaches 552,4 kN, which accounts for as much as 98% of the machine's maximum capacity (limit of 564 kN). This indicates that the machine is operating at the edge of its structural endurance, while simultaneously requiring a significant reduction in strip width.
- 3) Utilization of drive power: The drive power during the leveling of DP steel reaches 16,3 kW, which, given the limit of 16,5 kW, leaves a safety margin of only 1,2%. This indicates that power is the most critical parameter limiting process efficiency for high-strength steels.
- 4) Reduction in strip width: To enable the leveling process, a significant reduction in strip width is necessary: by 33,3% for HSLA steel (1000 mm) and by 43,3% for DP steel (850 mm) relative to the original design assumption of 1500 mm.
- 5) Process efficiency: The process speed must be reduced from the baseline 50 m/min to 40 m/min for HSLA (a 20% decrease) and to 35 m/min for DP (a 30% decrease), which significantly impacts the total throughput of the production line.
- 6) Structural analysis of the bearing system: The identified load values on the rollers (especially for DP type materials) exceed the original design assumptions, which imposes an absolute necessity to conduct a new engineering analysis of the bearing system and roller supports. The force acting on roller No. 3 increases from 64,2 kN to 78,9 kN for DP materials. This represents an increase of nearly 23%, which, according to the theory of maximum load at this point, poses a direct threat to

the fatigue life of this component. However, this does not necessarily mean that the existing bearing and support system for the leveling rollers lacks the required safety margin.

- 7) Torque analysis: The total torque for DP steel increases by 22,8% (853,3 Nm) relative to the baseline parameters (695 Nm). Although this value remains within the machine's limit (980 Nm), when combined with the maximum power demand, it constitutes a high load for the drive transmission system.
- 8) Preliminary empirical validation revealed that the mathematical model slightly overestimates the drive power requirements (within a range of 2.4–6.0%) compared to actual industrial processing of S235JR and H400LAD test sheets. This discrepancy is attributed to the model utilizing conservative, upper-limit yield strength values specified by metallurgical standards. Accounting for the cumulative effects of fluctuating process variables (strip tension, surface condition) and manufacturing tolerances, the developed model is proven to be robust and reliable for machine design and retrofitting, while the observed interaction suggests a promising path for future comprehensive dynamic analyses under industrial conditions.

Although the calculations and the presented analysis indicate the theoretical feasibility of processing the new material groups, it will come at the cost of a significant reduction in production parameters and the operation of the machine under extreme conditions, which may shorten the lifecycle of the leveler's mechanical components. It should be noted that during the design process, every professional engineer incorporates a safety margin for the structure and the machine's constituent systems. In each case, the final decision will be a compromise between lowering the technological parameters of the production line (process speed, strip width) and investing in new equipment or a radical overhaul of the entire processing line.

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