Experimental investigations of the roll load and roll torque when high strength steel is roll formed

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Abstract

The cold roll forming process is a highly efficient process used to produce profiles for many applications, for example vehicles, buildings, domestic machines, etc. Therefore, its market share is increasing every year. Many of the above products are already today made of high strength steel and the usage of these materials will likely continue to increase.

The objectives of this project are to find how the roll load and roll torque are influenced by the yield strength of the material. Full-scale experiments have been performed. U-channels made of different materials from mild to ultra high strength steels have been formed. The roll torque is measured during the process using a torque sensor mounted between the tool and the power transmission. Used power is also calculated with help of the motor current. The roll load is measured with load cells mounted on both side of the roll forming tool.

The experimental result will increase the understanding of the specific conditions for roll forming steels with increasing yield strength. The result can be used to support the roll machine designer to choose machine elements and power unit for these applications. Furthermore, the result can also be compared with finite element simulations in order to improve and validate simulation models.

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Keywords: Cold roll forming; High strength steel; Roll torque; Roll load

1. Introduction

Roll forming is a bending operation where the bending occurs in several forming steps from an undeformed strip to a finished profile. Every forming step consists of a pair of forming tools that rotate and drive the strip forward during the forming. Today one can find roll formed products in many different fields as buildings, vehicles, furniture, etc. The use of the process increases continuously due to the efficiency of the process.

Despite the fact that roll forming is a common sheet metal forming process and used worldwide there are relatively few publications about the process. The explanation may be the complexity of the deformation behaviour in the process despite its visual simplicity. There are numerous factors which can influence the roll forming design, for example unlimited variation of the shape of the profile. Nevertheless, some researchers have developed simple models [1,2], and in a newly released book Halmos [3] described how this process can be used successfully.

Finite element simulations have been used a long time in sheet metal forming to develop forming tools. However, this has

not been the case for the roll forming processes due to limited computer capacity. Only in recent years has this become possible [4–6], and today roll forming computer aided engineering system [7], can offer simplified finite element models for simulations. From these models the roll load and roll torque can be received and compared with measurement and thereby validated.

Bhattacharyya et al. [8] suggested an analytic model for the roll load in a single roll station, Eq. (1), when a U-channel was formed:

$$F = s \sqrt{\frac{2t^3\theta^3a}{3\sin(\theta)}} \quad (1)$$

where t is the thickness, s the yield strength, a the flange length and θ is the bend angle.

The model was compared with measurements for mild steel and aluminium for different thickness and bend angle. The conclusion was that the error between the model and the measurements was within 0–20%.

The current work is an investigation of the roll forming of a U-channel of different sheet metals, ranging from mild to ultra high strength steel. Roll load and roll torque have been measured during the forming. The results from these measurements can

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be used to validate finite element models, can support the roll machine designer to choose machine elements and power unit when the strength of the material increases.

2. Experimental details

2.1. The roll forming mill

A standard roll forming mill [3] (Fig. 1) is used to investigate the roll load and roll torque. The mill has six forming stands and universal joint driven shafts are used to run the tools. The power unit is a 15 kW frequency controlled three-phase motor. No driven top shafts are used.

2.2. The measurement equipment

Two load cells of donut type from Honeywell Sensotec Sensors are mounted between the tools and the forming stands in order to measure the roll load (Fig. 1). The maximum roll load that the load cells can measure is 17,800 N. The roll torque is measured with a torque sensor from Burster, which can measure up to 75 Nm. The torque sensor is mounted between the power transmission and the lower forming tool (Fig. 1). An encoder is used to measure the velocity of the profile. The motor current is measured by a frequency changer.

The data acquisition equipment is from NATIONAL INSTRUMENT™ where the used software is LabVIEW™.

2.3. The profile

The U-channel is formed in four steps from an undeformed strip to a bend angle of 80°. The undeformed strip has a width of 84 mm and a thickness ranging from 1.0 to 1.5 mm. The bending method is “constant arc length” [9] which means that the bend radius will be different for every forming step but the arc length of the bend corner will be constant. The final profile, bend angle 80°, has a flange length of 23.3 mm, a web of 23.3 mm and a final radius of 5.55 mm at the neutral layer when 1 mm strip is formed.

2.4. The material

Seven different materials have been tested, four carbon steels and three stainless steels (Table 1).

Fig. 1. A standard roll forming mill is used to do experiments, the roll load is measured with load cells and the roll torque is measured with a torque sensor during a forming of different steels.

Table 1

The materials that have been tested are Docol, DC01 (carbon steel) and HyTens, SS2333 (stainless steel)

Material	Thickness (mm)	$R_{p0.2}$ (MPa)
DC01	1.46	193
Docol 800DP	1.48	533
Docol 1200M	1.46	1129
Docol 1200M	1.22	1119
HyTens 1200	1.0	1018
SS2333	1.0	301
HyTens X	1.0	286

2.5. The experimental set-up

The strip is formed through a single forming step with varying bend angles, 20°, 40°, 60° and 80°, during the forming the load and torque are measured. The forming passes before and after the single step are only used as flat rolls (0°–0°–0°). This is done in order to eliminate the influences on torque from other forming steps. The bending angle increment is dependent on the amount of spring back from the previous forming step.

The load and the torque are dependent on the tolerance between the thickness of the formed material and the roll gap between the tools. The load and the torque will be very large if the clearance between the upper and lower tool is too small. To avoid this, the profile is rolled in between the tool and the roll load is increased until the roll gap is between 0.1 and 0.15 mm larger than the thickness of the formed material, this is checked with a feeler gage.

The measurement starts when the profile rests on both the flat rolls before and after the forming step. The velocity of the profile that is used during the measurement is 9.7 m/min. A lubricant is used in abundance and the surface finish is $R_z = 1 \mu\text{m}$.

3. Result

In Fig. 2 are the measured roll load and the roll torque presented for Docol 1200 M, thickness 1.46 mm. The mean value is calculated for every experiment in Fig. 2 during the sample time 30 to sample time 60. A new mean value and standard deviation is then calculated for the mean value from experiments 1 to 3 for the load and the torque. These values are presented for all used materials in Table 2.

3.1. Models

In the experiments, for example bend angle 60°, have materials with different thickness and virgin yield strength been used, if one assumes that only these parameters influence the load and the torque a model can be created as Eqs. (2) and (3):

$$F_{\text{Load}} = k_1(\theta)t^{k_2}s^{k_3} \quad (2)$$

$$T_{\text{Torque}} = k_4(\theta)t^{k_5}s^{k_6} \quad (3)$$

where t is the thickness of the material, s the yield strength of the material, k_i the constants and exponents and θ is the used bend angle, in this case 60°.

In Fig. 3 are the models, Eqs. (2) and (3), compared with experiments when the bend angle 60° is used. The constants and the exponents in the Fig. 3 are $k_1(\theta) = 88$, $k_4(\theta) = 0.38$, $k_2 = k_5 = 2.1$ and $k_3 = k_6 = 0.57$. This is somewhat different from

Fig. 2. The roll load and roll torque is measured for three different experiments. The used material in the figure is Docol 1200 M, thickness 1.46, at the bend angle 60°.

the analytic model for the load as in Eq. (1), Bhattacharyya et al. [8].

3.2. Power

The motor current is measured during the forming of Docol 1200 M, thickness 1.46 mm. All forming passes are engaged at the same time and the current increases during the forming with 0.6 ± 0.1 A.

The three-phase power (P_{engine}) used to forming the sheet can be calculated as:

$$P_{\text{engine}} = \sqrt{3} U \Delta I \cos(\varphi) \quad (4)$$

where $U = 400$ V, $\Delta I = 0.6 \pm 0.1$ A and $\cos(\varphi) = 0.83$.

Which gives a power of:

$$P_{\text{Engine}} = 0.345 \pm 0.057 \text{ kW} \quad (5)$$

Table 2
Seven different materials have been formed with the bend angles 20°, 40°, 60° and 80°

Material	Bend angle (degrees)	Mean value		Standard deviation	
		Load (N)	Torque (Nm)	Load (N)	Torque (Nm)
HyTens X	20	1818	9.2	59	0.6
SS2333	20	2039	13.3	591	1.7
HyTens 1200	20	2857	11.4	299	1.6
Docol 1200 M	20	8503	30.1	412	1.6
Docol 800 DP	20	5247	28.4	258	1.2
DC01	20	3846	28.8	199	3.8
Docol 1200 M (1.22 mm)	20	5399	21.5	417	0.7
HyTens X	40	2228	12.1	141	0.7
SS2333	40	2418	12.9	26	0.2
HyTens 1200	40	4500	21.2	195	1.0
Docol 1200 M	40	10001	54.1	750	2.6
Docol 800 DP	40	8203	42.4	547	2.4
DC01	40	4877	31.1	158	1.2
Docol 1200 M (1.22 mm)	40	6825	33.5	1168	4.8
HyTens X	60	2038	8.4	206	0.3
SS2333	60	2121	9.0	286	1.1
HyTens 1200	60	4689	16.8	394	1.3
Docol 1200 M	60	10148	45.7	704	2.8
Docol 800 DP	60	7946	36.2	384	1.0
DC01	60	4992	23.0	863	1.6
Docol 1200 M (1.22 mm)	60	6521	29.5	522	2.4
HyTens X	80	2752	15.4	205	1.2
SS2333	80	2628	16.3	275	1.3
HyTens 1200	80	4536	25.2	344	0.7
Docol 1200 M	80	9575	61.3	372	2.0
Docol 800 DP	80	8368	51.9	42	0.3
DC01	80	4543	27.0	527	11.0
Docol 1200 M (1.22 mm)	80	7260	47.1	1109	2.1

The forming load and the forming torque are measured for all cases.

Fig. 3. The models, Eqs. (2) and (3), are compared to the experimental result for the used materials.

The power calculated with help of measured total torque (T_{Total}) and measured forming angle velocity is:

$$P_{\text{torque}} = T_{\text{Total}}\omega \quad (6)$$

where total torque and forming angle velocity for bend angles 20° , 40° , 60° and 80° (Table 2) is:

$$\begin{aligned} T_{\text{Total}} &= 30.1 + 54.1 + 45.7 + 61.3 = 191 \text{ Nm}, \\ \omega &= 2.156 \text{ rad/s} \end{aligned} \quad (7)$$

Which gives a power of:

$$P_{\text{Torque}} = 0.411 \text{ kW} \quad (8)$$

4. Conclusion

The results from the experiments can be used to validate and calibrate finite element models. Calculated force will agree fairly well with the measured load provided the material model is correct. The material model can be calibrated by separate material testing. Then the friction coefficient can be adjusted until the torque also agrees well. A lubricant is used in abundance and the surface finish is $R_z = 1 \mu\text{m}$ which should give a friction coefficient between 0.05 and 0.1 for Coulomb friction.

Eqs. (2) and (3) give the torque and force required for the bending in a forming step as a function of thickness, material

virgin yield strength and bending angle. The calibration of the model gave a good agreement with measurements according to Fig. 3. A consistency check of the measured torque by power comparisons (Eqs. (5) and (8)) in Section 3.2 was done and showed reasonable agreement.

A low production velocity used in the experiments ($v = r\omega$, $r = 0.075 \text{ m}$, $\omega = 2.156 \text{ rad/s}$, $v = 9.7 \text{ m/min}$). A more common production speed is 30–40 m/min. A speed of 40 m/min gives a power of 1.7 kW. Thus about 0.5 kW is required for every forming step when normal production speed is used under conditions similar to those in the current study. It is possible to use of Eq. (3) to estimate the increase in power consumption when changing, for example, the yield strength of the formed material.

Acknowledgements

The author thanks ORTIC AB, Swedish Knowledge Foundation, Jernkontoret and Dalarna University for their technical and financial support.

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