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Experimental study on the effects of clearance and clamping in steel sheet metal shearing^{†‡}

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Abstract

Shear cutting is common within several sheet metal industry processing steps, e.g. in cut to length lines, slitting lines, end cropping. Shearing is fast and cheap relative to competing cutting methods like laser and plasma cutting, but involves large forces on the equipment that increase with increased sheet material strength. Accurate shear experiments are a prerequisite to increase the knowledge of shearing parameters, improve industrial shearing, and provide data for validation of numerical shear models. Here, the two shear parameters clearance and clamp configuration, identified as important to the shear results, were studied in an experimental set-up with well defined tool movement and high measurability of tool position and force. In addition to force measurements, the sheared edge geometry was characterized. Steels of low, medium, and high strength were selected for the study. Throughout the experimental study, the shear tool penetration before fracture decreased with increased material strength. The required shear force decreased and the force attempting to separate the two shear tools increased when one side of the sheet was left unclamped and free to move. Further, the maximum shear force increased with decreased clearance. Clearance changes were small and moreover continuously measured during all shear experiments.

Keywords: sheet metal, experiment, shearing, cutting, force, clearance

1 Introduction

Shearing is a fast and cheap method for sheet metal cutting compared with alternative methods such as laser and plasma cutting. In the sheet metal industry, shear cutting is often used in various processing steps including cut to length,

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slitting and end cropping. The constant development of sheet metals toward higher strength and formability leads to increased forces on the shear equipment and tools. Increased knowledge and a refined process becomes important to maintain tool life and achieve the desired sheet tolerances. Experimental data are needed to understand and model the shearing mechanisms and also for validation of numerical models. Published experimental data of forces during the shearing process are nevertheless rare and in particular never include the force that separates the two shear tools. In straight cuts with parallel tools that force is transferred through the tools to the surrounding structure while it can be limited to the punch and die in the similar blanking process. Some noticeable publications which include measurements of force on the rotational symmetric blanking process are made by Crane (1927) where forces are correlated to edge geometries, by Oldenburg (1980) where effects of sheet clamping are studied, and by Hambli et al. (2003) where tool wear are studied. Furthermore, most studies do not consider friction forces in the equipment or the tool clearance variations during the shear process.

Based on the above mentioned deficiencies, the purpose of this study was to provide accurate measurements of shear forces without friction losses together with measurements of clearance variations during the shear process. The measurements were recorded by the method and set-up developed and described in detail by Gustafsson et al. (2014), and also briefly described in the following section. In this study, shear experiments were performed to study the effects of clamping and clearance on the tool forces.

2 Methods

Basic shear geometries are schematically shown in figures 1 and 2 together with definition of the coordinate system used. Gustafsson et al. (2014) developed a symmetric experimental set-up, shown in figure 3, where each side consists of one fixed and one floating tool. Two sheets were simultaneously sheared to achieve a stable clearance and balanced forces in the x -direction, F_x . With F_x balanced, no guides were required and their inevitable friction losses were avoided. Thus, the tool forces were measured with high accuracy. The tool forces F_x and F_y were recorded via strain gauges glued onto the strut and the pillars of the set-up, as shown in figure 3. Further, the tool displacements were obtained from image analysis of digital camera images of the speckle painted tools, as thorough described by Gustafsson et al. (2014).

According to results from the perturbation analyses performed by Gustafsson et al. (2014), clamping and clearance are two of the most important shear parameters. The effects of clearance and clamping variations were evaluated through shearing of three sheet materials with two clamping configurations, one side or both sides, and clearances according to table 1. Clearances were chosen in a large interval to cover the, by manufacturer, recommended clearance for each individual material with comfortable margin at both ends. Clamping forces were not measured, but were large enough to prevent separation between sheet and shear tools. All marked combinations in table 1 were sheared in both the dual clamped configuration as shown in figure 3 and the single clamped configuration with the outer clamps removed. The geometry of the sheared edge was characterized in terms of the four characteristic zones introduced by Atkins

Figure 1: Schematic 3D representation of shear geometry with definition of the coordinate system used. (Gustafsson et al., 2014)

Figure 2: Schematic representation of the shear geometry and boundary conditions. The moving shear tool and corresponding clamp have the same velocity v in the y -direction. Reaction forces on the moving tool as result of the velocity v are F_x and F_y . Definitions of sheet thickness h , clearance c , shear tool radius r and tool displacements U_x and U_y are shown in the magnified area (Gustafsson et al., 2014).

Figure 3: Schematic front view of the experimental set-up showing strain gauge positions as black squares. Sheet strips were clamped on both sides (Gustafsson et al., 2014).

Table 1: Matrix of clearances used for shearing the three sheet metal grades in the experimental study. Clearances are also shown relative the sheet thickness h .

Clearance [mm]	Low strength	Medium strength	High strength
0.35		0.07 h	
0.42	0.07 h		
0.64	0.11 h	0.13 h	0.11 h
1.07		0.22 h	0.18 h
1.44			0.24 h

(1981) and defined in figure 4. According to Hilditch and Hodgson (2005), the extent of the zones depend on the shear geometry as well as the material properties.

Three materials were used in the study: a mild strength (LS) high formability steel, a medium strength (MS) construction steel, and a high strength (HS) wear plate steel. Steel properties are shown in table 2 and figure 5. Mechanical properties shown in table 2 were obtained from uniaxial tensile tests and the

Figure 4: Sheared edge characteristic zones shown on sheet cross-section (Gustafsson et al., 2014).

Table 2: Properties of sheet metal grades used in the experimental evaluation. Thickness is given with minimum and maximum values representative for the encountered variations.

Material strength	Yield strength, Rp02 [MPa]	Tensile strength, Rm [MPa]	Elongation, A80 [%]	Thickness [mm]
Low	210	300	40	5.83 ± 0.05
Medium	450	520	25	4.95 ± 0.05
High	1080	1260	7	6.08 ± 0.01

Figure 5: Flow stress curves for the low, medium and high strength material grades in three directions obtained from compression test data with the assumptions of constant volume and cylindrical sample shape throughout the entire test.

sheet thickness was measured on the sheared samples. The flow stress curves shown in figure 5 were obtained from uniaxial compression tests of cylindrical samples, approximately 6.0 mm long and 3.2 mm in diameter, that were prepared from the sheet in three directions. Each flow stress curve is representative for a series of three tests on each combination of material and direction. The rolling direction, the sheet thickness direction, and the in sheet plane direction that is transverse to the rolling direction correspond to the x -, y - and z -directions respectively. All compression tests were performed according to the method described by Gustafsson et al. (2014). For the tested material grades, the flow stress curves show some anisotropy between the thickness direction and the two in plane directions. The HS material also shows anisotropy between the in plane directions at plastic strains below 0.3.

Two sheet strips with 55.0 mm width and approximately 250 mm length were prepared and sheared in each experiment.

Polished shear tools with $220 \pm 5 \mu\text{m}$ radius were used in all experiments. During shearing, the tool surfaces were amply lubricated with an industrial grease containing zinc additives, in order to achieve consistent and repeatable contact conditions.

Finite element (FE) simulations were used to study phenomenons and tendencies seen in the experiments. Simulations offer detailed studies of the shear process and are valuable for the understanding of mechanisms in shearing. All analyses were performed with a commercial general purpose FE software and the same 2D plane strain model, with geometry and boundary conditions according to figure 2, as motivated and validated against experiments by Gustafsson et al. (2014). An isotropic elastic/plastic sheet material with hardening pursuant to the exponential model $\sigma_Y = K\bar{\varepsilon}_p^n$ by Hollomon (1945) was used in the FE analysis. Here, σ_Y is the yield stress, $\bar{\varepsilon}_p$ is the effective plastic strain and K and n are material specific parameters selected to represent the MS steel grade. Based on the fairly isotropic flow stress shown in figure 5, an isotropic model were considered sufficient for the present study. Previous simulations with this model by Gustafsson et al. (2014) have shown good agreement with experiments in term of forces. Tools and clamps were considered elastic and all materials were assigned Poisson's ratio equal to 0.3 and Young's modulus equal to 210 GPa. Contacts were modeled with a 2D surface to surface penalty formulation and the Coulomb model was used as friction law. The finite element size in the shear area was selected so that the tool radius was represented by three elements. All elements were four-noded and fully integrated. An adaptive remeshing was applied to lower the element distortion in the plastic deformed zone. The simulations were moderated with a constant tool acceleration because of the numerical advantages in avoiding velocity steps.

3 Results

Recorded forces from shear experiments on the three sheet materials at chosen clearances are shown in figure 6. Clearances were selected according to table 1 and two clamping configurations, one and two clamps, were used. For the three sheet metal grades examined, F_x increased and F_y decreased when one clamp was removed. With two clamps, a pronounced decrease in F_x is seen after the initial increase. At larger U_y , the force F_x show tendencies to increase again, but only the LS sheet in figure 6a sustain enough penetration for the effect to be clearly visible. There is an increase in F_y with decreased clearance, but for some material and shear parameter combinations, the differences in F_y attenuates and is also reversed at large U_y . Also, at large U_y , a small but consistent increase in F_x is seen with decreased clearance except for the one clamped shearing of the LS sheet.

All force curves in figure 6 are trimmed to the last sample before fracture, and therefore they only represent an indication of the fracture point. With the constant time sample used in all measurements combined with a throughout accelerating shear process, the shear tool displacement between two samples at the point of fracture can reach several tenths of a millimeter. Notable regarding the figures is also that line markers are merely for curve identification and only represent a fraction of the sampled points.

Clearance change, U_x , between the tool edges are shown in figure 7. Common for almost all combinations of material, clearance, and clamping configuration, are small changes in U_x after an initial stabilizing phase during the first 0.5 mm of y -directional displacement. By correlating U_x to the respective F_y in figure 6,

Figure 6: Measured forces from shearing the (a) low strength, (b) medium strength, and (c) high strength sheet metal grades at different clearances and clamp configurations.

the initial change in U_x can be related to initial build-up of F_y . Also common for all measurements are larger U_x , i.e. larger clearance increase or smaller clearance decrease, for experiments with one clamp relative two clamps.

Duplicate experiments were done at some clearances to estimate the total error and assess repeatability. Forces from these tests are shown in figure 8. Reshimming of the shear tools between the experiments yields clearance variations in the range 0.01–0.02 mm. According to figure 8, the deviations in forces for the HS sheet are close to the 1 % experimental set-up error range determined by Gustafsson et al. (2014), but force deviations for the MS and LS sheets are up to 5 %. All force deviations are close to constant over the entire shearing, i.e. independent of U_y .

Growing plastic zone, material hardening, load carrying area reduction, and changed contact conditions are all contributing to the characteristics of the obtained force curves. FE simulations were applied to reveal contact forces on the tool zones defined in figure 9. Boundaries were positioned so that zone 2 represented the tool part that is rounded with radius r . The position of the boundary between zone 3 and zone 4 is not critical because the sheet separates from the tool over a large area between the tool edge and the clamp during shearing. Since the friction coefficient is somewhat uncertain in the experiments, all simulations were performed with three friction coefficients: 0.05, 0.10, and 0.15. Tool contact forces divided into x - and y -components for each zone are shown for the one clamped and two clamped case in figures 10 and 11 respectively. Due to the geometry shown in figure 9 the components $F_x^{\text{zone } 1}$, $F_x^{\text{zone } 3}$, $F_x^{\text{zone } 4}$ and $F_y^{\text{zone } 5}$ are normal forces; $F_y^{\text{zone } 1}$, $F_x^{\text{zone } 3}$, $F_x^{\text{zone } 4}$ and $F_x^{\text{zone } 5}$ are friction forces; and $F_x^{\text{zone } 2}$ and $F_y^{\text{zone } 2}$ are combinations of normal and friction forces. Evidently, the major part of the total force is transmitted close to the tool radius in the normal direction of the contact surface. Also, due to coupled process conditions, the normal forces are effected by changes in friction coefficient. During shearing, the induced rotation of the sheet results in the force $F_y^{\text{zone } 5}$ on the clamp and the force on the tool opposite to the clamp, $F_y^{\text{zone } 4}$, is therefore small although there is still contact in zone 4. Moreover, the observed decrease in $F_x^{\text{zone } 3}$ combined with the steadily increasing $F_x^{\text{zone } 1}$, after the initial tool displacement without contact in zone 1, result in the characteristic dip in the total x -directional force F_x . The dip is most pronounced in the two clamped case, figure 11, especially in combination with high friction coefficients.

Images of the sheared edges were captured in the z -direction and are shown in figures 12–14. Some of the images show dark shadows as result of an optical effect when some part of the lens captures an unfocused image down the sheared edge. The effect is most visible in columns 2 and 4 to the left of the sheared edge. Rollover and shear zones were projected on the y -axis and measured as shown in figure 4. The measurements presented in table 3 were taken on the clamped side in the one clamped configuration. Table 3 also presents the plastic zone size measured as x -axis projection of the rollover. FE-simulations revealed that the maximum extension of the plastic zone along the x -direction is found on the sheets rollover surface. Uncertainties in the plastic zone measurements were much larger than in rollover and shear zone measurements since the slope of the rollover gradually approached zero and no distinct transition existed. Approximately, the plastic zone size measurements are correct within 0.5 mm. The size of the rollover and plastic zone always increased with increasing clearance, but the shear zone size decreased with increasing clearance; an exception from

Figure 7: Measured clearance change, U_x , at shear tools edges from shearing the (a) low strength, (b) medium strength, and (c) high strength sheet metal grades at different clearances and clamp configurations.

Figure 8: Measured forces from repeated shear experiments on the (a) low strength sheet at 0.64 mm clearance, (b) medium strength sheet at 0.64 mm clearance, and (c) high strength sheet at 1.07 mm clearance.

Figure 9: Schematic representation of the defined contact zones between sheet strip and tools. The border between zone 3 and zone 4 is positioned in the region where tool and sheet are not in contact.

Table 3: Rollover, shear, and plastic zone sizes for the low, medium, and high strength sheet metal grades sheared at different clearances and clamping configurations.

Material strength	Clearance [mm]	One clamp			Two clamps		
		Rollover [mm]	Shear zone [mm]	Plastic zone [mm]	Rollover [mm]	Shear zone [mm]	Plastic zone [mm]
Low	0.42	1.0	2.6	4.0	1.0	4.0	3.8
Low	0.64	1.2	2.4	4.2	1.2	2.5	4.2
Medium	0.35	0.7	1.3	2.6	0.8	1.8	3.0
Medium	0.64	0.8	1.6	3.6	0.8	1.7	3.0
Medium	1.07	1.0	2.4	3.7	1.0	1.6	4.0
High	0.64	0.4	1.6	1.8	0.4	1.3	2.0
High	1.07	0.5	1.3	1.8	0.5	1.2	2.2
High	1.44	0.7	1.3	2.4	0.7	0.9	2.8

this trend was one clamped shears of the MS steel grade. With the applied measurement method, the size of rollover and plastic zones was independent of the clamping configuration. Differences in shear zone size between the clamping configurations were established but without clear trends.

Shearing with only one clamp resulted in an additional plastic deformation of the free end of the strip, outside the burr, where the contact force is concentrated. This deformed zone reflects the maximum angle between the strip and the shear tool before fracture.

Clamped strip ends showed a similar edge geometry in one clamped shears and two clamped shears. Sometimes, however, F_x in one clamped shearing was twice as large as in two clamped shearing. Thus, edge geometry could not be used to estimate the stress state during shearing.

Rollover, shear and plastic zone sizes tended to decrease with increasing material yield and tensile strength.

Figure 10: Simulated contact force components for the one clamp configuration, separated in various zones (defined in figure 9) of the sheet strip to tool contact. Each panel shows results at three friction coefficients μ . For the total y -directional force component F_y and zone 3 y -directional force component $F_y^{\text{zone } 3}$, the initial, almost linear, rise from zero force is hidden to allow an equal force span of 50 kN in all subplots.

4 Discussion

Contributions to the total displacement of the tool in the x -direction are mutual displacement of the inner shear tools and strut relative the two outer, elastic deformation of the strut, and rotation of the tools. For instance, the elastic deformation of the strut was $7\text{ }\mu\text{m}$ when $F_x = 40\text{ kN}$. The optically measured total tool displacement was separated in translations of the tool mass center in the x - and y -directions and rotation around the z -axis. When shearing the LS and MS strength sheets, the clearance decrease originating from rotations

Figure 11: Same as figure 10, but for the two clamps configuration.

were less than $10\text{ }\mu\text{m}$. This observation suggests that the clearance change in figures 7a and b, must be mostly due to mutual displacement of inner shear tools relative the two outer ones. Shearing of the HS sheet resulted in larger rotations, about 0.1 mrad , which caused a decrease of approximately $50\text{ }\mu\text{m}$ in clearance at tool edges and significantly influenced U_x in figure 7c. The observed rotations originated from a larger ratio of F_y/F_x than the one used to determine the tool positions relative to the pillar center in the x -direction during the experimental set-up design. With knowledge of the F_y/F_x ratio, the tools can be positioned to avoid tool rotation. However, the shear tool position suitable for the MS material was used for shearing all three material grades. The differences in U_x between the one and two clamp configurations probably depend on two different phenomena. First, during the initial stabilizing phase where $U_y < 0.5\text{ mm}$, the mutual displacement of inner shear tools relative the two outer ones is effected

Figure 12: Images in the z -direction of sheet edges from the low strength sheet sheared with different clearances: 0.42 mm in row 1; 0.64 mm in row 2. Columns 1 and 2 correspond to the one clamp configuration, where the free end is shown in column 1, and columns 3 and 4 correspond to shearing with two clamps.

Figure 13: Same as figure 12, but for the medium strength sheet. Clearances are: 0.35 mm in row 1; 0.64 mm in row 2; 1.07 mm in row 3.

Figure 14: Same as figure 12, but for the high strength sheet. Clearances are: 0.64 mm in row 1; 1.07 mm in row 2; 1.44 mm in row 3.

by the clamping. Secondly, after the stabilizing phase, the small differences in U_x originate from differences in the F_y/F_x ratio between single and dual clamp configurations.

Despite a well defined experiment and accurate measurements, there were force deviations between repeated experiments as shown in figure 8. These deviations likely originated from property variations of the sheared sheet strips. According to the perturbation analyses performed by Gustafsson et al. (2014) the measured variations of thickness, shown in table 2, cannot result in force variations of the observed magnitude. Inhomogeneous mechanical properties or local variations in friction coefficient between sheet and tool are further possible contributions to the observed force variations. The perturbation analyses also indicate that global variations in the friction coefficient mainly effects F_x , whereas the present measured force variations were most pronounced in F_y and almost independent of U_y . Hence, variations of mechanical properties in the sheet are the most probable explanation to the measured force deviations.

Shearing of the MS sheet with 1.07 mm clearance and one clamp resulted in an distinctly large penetration and burr formation before fracture compared with the other experiments on the same material at smaller clearances. Expressed relative to the sheet thickness h , a clearance of 1.07 mm is larger than $0.20h$ and apparently too large for the material grade and clamping configuration.

With the larger F_x observed in one clamped shears compared to two clamped shears, the remaining material between the shear tools experience large tensile stresses and a shear stress is introduced in the xz -plane at the tool radius. Large shear stresses may increase the risk for mode II fractures (a shear stress acting perpendicular to the crack front) on the edge. Hubert et al. (2010) concludes that edge cracks in combination with a rolling operation is a problem, especially for soft materials. According to the results of the simulations shown in figures 10 and 11, the force components $F_x^{\text{zone } 1}$ and $F_x^{\text{zone } 2}$ were larger for the one clamped case compared with two clamped case except for the first 0.5 mm and possibly the last 0.5 mm in the simulations. At around $U_y = 1$ mm, the component $F_x^{\text{zone } 3}$ was also lower for the one clamped case compared with the two clamped case. With the above arguments, mode II edge cracks should be suppressed with clamping of both sides of the sheet.

As shown in figures 10 and 11 the minimum and maximum values of $F_x^{\text{zone } 3}$ scaled proportional to the friction coefficient. The behavior suggests a sliding contact, and the reversed sign of forces imply reversed relative movement. However, $F_x^{\text{zone } 3}$ was less than $\mu F_y^{\text{zone } 3}$ (where μ is the Coulomb friction coefficient) except for small values of U_y . Possibly the phenomenon is the result of a varying contact pressure in zone 3 and a sticking contact closest to zone 2 where the contact pressure is largest.

5 Conclusions

This study demonstrated how to generate accurate experimental data that are a prerequisite for validation of numerical shear models. More specifically, based on the experimental shear study supported by FE simulations, the following conclusions were made:

- The force F_x was higher, but F_y was lower, in shearing with one-clamp compared with shearing with two-clamps. In other words, the force required to shear the sheet decreased, but the force that acts to widen the tool clearance increased, when one clamp was used instead of two clamps.
- There was a clear trend for increased maximum shear force, F_y , with decreased clearance.
- The clearance was stable during the shear process and the small existing variations of the clearance could be measured.
- The characteristic dip in F_x was an effect of variations of the contact conditions during the shear process.
- The size of both the rollover and the plastic zone increase with increasing clearance.

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