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Design and validation of a sheet metal shearing experimental procedure^{†‡}

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Abstract

Throughout the industrial processes of sheet metal manufacturing and refining, shear cutting is widely used for its speed and cost advantages over competing cutting methods. Industrial shears may include some force measurement possibilities, but the force is most likely influenced by friction losses between shear tool and the point of measurement, and are in general not showing the actual force applied to the sheet. Well defined shears and accurate measurements of force and shear tool position are important for understanding the influence of shear parameters. Accurate experimental data are also necessary for calibration of numerical shear models. Here, a dedicated laboratory set-up with well defined geometry and movement in the shear, and high measurability in terms of force and geometry is designed, built and verified. Parameters important to the shear process are studied with perturbation analysis techniques and requirements on input parameter accuracy are formulated to meet experimental output demands. Input parameters in shearing are mostly geometric parameters, but also material properties and contact conditions. Based on the accuracy requirements, a symmetric experiment with internal balancing of forces, is constructed to avoid guides and corresponding friction losses. Finally, the experimental procedure is validated through shearing of a medium grade steel. With the obtained experimental set-up performance, force changes as result of changes in studied input parameters are distinguishable down to a level of one percent.

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

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1 Introduction

Sheet metal shearing is common within several processing steps in the sheet metal industry, and increased knowledge is desirable in order to improve the processes. Shearing has speed and cost advantages over competing cutting methods like laser and plasma cutting, but involves large forces on the equipment and large strains in the sheet material.

Numerical models to predict forces and sheared edge geometry for different sheet metal grades and different shear parameter set-ups are desirable. For new sheet metal grades, numerical shear models are efficient for finding appropriate shear parameters without the need for time consuming and expensive live tests in the production. In order to allow for validation of numerical models, accurate experimental data is beneficial. Though industrial shears may include some force measurement possibilities, the force is most likely influenced by friction losses between shear tool and point of measurement, and thus not showing the actual force applied to the sheet. Force measurements with load cells close to the shear tools, before impact of guiding contacts, are associated with loss in accuracy of shear tool position.

Crane (1927) provides experimental force data from studies of the axisymmetric blanking process and investigates effects of geometry and material grades. However, the blanking and shearing processes differ in boundary conditions, where the solid punch in blanking implies an inherent stiffness, i.e. a change in the total clearance between punch and die is only possible through a radius change of the punch and/or the die.

This work aim to develop a procedure for experimental evaluation of shearing processes and includes the design, build and validation of a well defined experimental set-up with high measurability and reproducible output. During the design phase, finite element (FE) simulations are used frequently for perturbation analyses of shear parameters and also dimensioning of the experimental set-up.

1.1 Shear geometry

Fundamental shear geometry is represented in figures 1 and 2, where the sheet metal is sheared between two shear tools and held in place by one or two clamps. Here, the geometric properties defined are sheet thickness h , shear tool radius r , clearance c , x -directional tool displacement, i.e. clearance change, U_x and y -directional tool displacement U_y . Shearing of wide sheet strips generally includes the rake angle, created by rotation of one shear tool around the x -axis in figure 1. Oldenburg (1980) concludes that use of rake angles limits contact length and forces but distorts the edge through additional strains in the sheared material.

In general, existing shear settings effect the sheared edge geometry, which in turn is important for aesthetics, sharpness and the tendency to initiate cracks. Atkins (1981) discusses the sheared edge surfaces in terms of four characteristic zones, i.e. rollover, shear, fracture and burr zones, as shown in figure 3. Rollover and shear zones arise from the plastic deformation of the sheet when penetrated by the shear tools, while the appearance of fracture and burr zones are determined by the crack propagation characteristics during fracture. Small shear zones and large fracture zones are specific for shearing of high strength steels. Burrs and rough fracture zones complicate the following processing through in-

Figure 1: Schematic 3D representation of shear geometry with definition of the coordinate system used.

Figure 2: Schematic representation of the shear geometry and boundary conditions. Here, the moving shear tool and corresponding clamp have the same velocity v in the negative 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.

Figure 3: Sheared edge characteristic zones shown on sheet cross-section.

adequate tolerances that may imply additional machining and sharp edges that may damage equipment or even cause injuries. Wu et al. (2012) discuss characterization of edges due to sheet metal shearing and develop a method for post shear strain evaluation through analyses of sheet edge microstructure. Also, sub-cracks in the sheared edge surface are observed by the authors.

Within most shear processes, the clearance between shear tools is usually governed by sheet properties, e.g. metal grade or thickness. Clearance and clamping have large impact on the sheared edge geometry. Thorough clamping of the sheet close to the shear tools, is important to reduce the strains and distortions of the sheared edges. Ideally, cracks will start from each tool radius and meet inside the sheet. Depending on the fracture zone size and crack propagation angle, clearance is set to allow the cracks to meet without overlap. Hambli et al. (2003) measure the blanking force and tool wear for clearances between 5 % and 20 % in experiments on a carbon steel, and suggest 10 % clearance for low force and tool wear. Hilditch and Hodgson (2005) employ experiments on shearing and conclude that both rollover and burr increases with greater clearance and that the rollover size depends on work-hardening in addition to clearance.

1.2 Shear parameters

Shear processes transfer input to output parameters as represented by figure 4. Geometric input parameters and output forces are defined in figure 2. In case of FE simulations, additional input parameters like mesh, mass scaling and other nonphysical parameters are added. Studies of the rake angle are deliberately excluded in order to approach plane strain. With parallel tools and suppression of edge effects through large sheet width to thickness ratio, plane strain is assumed to be representative for the process.

2 Design methods

In order to assess the quality of the proposed experimental method, the following sub-tasks are considered. First, FE simulations of shearing are performed, where the sensitivity of the considered output parameter in terms of the different input parameter perturbations are studied. Based on results from the perturbation analyses, a criteria on acceptable magnitude of the experimental set-up tolerances are identified together with a measure of the needed measurement precision. Secondly, an experimental set-up that fulfills the identified requirements is designed. Finally, the simulated and experimentally obtained results are compared for the case of shearing a common steel grade sheet.

Figure 4: Block representation of the shear process, listing main input parameters and considered output parameters.

Through consideration of measurability and reasonable input variation, the perturbation analyses also identify input parameters relevant for further studies. Primarily, the simulations are evaluated through resultant forces on tools, but the sheet material strain field is also considered although representing a more subjective quantity, hard to quantify.

2.1 Finite element model

All the FE perturbation analyses are performed with a commercial general-purpose finite element software and utilize a 2D plane strain model with geometry and boundary conditions according to figure 2. Sheet and tools are coarsely meshed except in vicinity of the tool radius, where the mesh is denser in order to dissolve the shear tool radius itself and gradients in state variables. All plane strain elements are four-noded and fully integrated. Adaptive remeshing of the plastic deformed zone is applied to prevent severe element distortion. Contacts are modeled with 2D surface to surface formulation and due to the assumption of lubricated surfaces, the friction coefficient is set to 0.1 concerning both static and dynamic friction. The tools are considered elastic while an isotropic elastic/plastic material model is assumed constitutive for the sheet metal. Poisson's ratio equal to 0.3 and Young's modulus equal to 210 GPa are used as elastic parameters for all materials. Hollomon's exponential hardening law (Hollomon, 1945), which states the yield stress as $\sigma_Y = K\bar{\varepsilon}_p^n$, is applied to describe the plastic hardening of the sheet material. Here, $\bar{\varepsilon}_p$ is the effective plastic strain and K and n are material specific parameters.

All simulations are displacement controlled and, because of numerical advantages in avoiding steps in velocity, all perturbation analyses are run at constant acceleration of 100 mm s^{-2} .

3 Perturbation analyses results

Adaptive remeshing is applied in simulations and results in force dips/peaks in conjunction with each remesh step. However, the dips/peaks are short and the remeshing is tested for convergence with refined remesh steps. For clearness, all graphs presenting simulated results show forces with a first order Butterworth

Figure 5: Force curves from the FE based perturbation analysis, showing the influences of clearance variations. Six clearances, 5 %, 10 %, 11 %, 15 %, 20 % and 25 % are shown and all arrows are pointing in direction of increased clearance.

Figure 6: Schematic representation of the tool to sheet penetration at equal U_y but different clearance. At small clearance (left), the deformation is localized while at large clearance (right), a larger area is deformed and only part of the tool radius is in contact with the sheet.

low pass filter at the normalized cutoff frequency of 0.02 half-cycles per sample applied. Still, some waviness is seen in most graphs. When reading the graphs, U_y should be related to the sheet thickness of 5 mm, used in all perturbation analyses.

Clearance changes result in distinct force changes over the entire process as shown in figure 5. Even small changes, like an increase from 10 % and 11 %, cause distinguishable force changes. Simulations also show that the actual tool into sheet penetration at equal tool displacement U_y , decreases with increased clearance as illustrated in figure 6. With increased clearance, deformation is activated in a larger area and consequently the rollover zone increases in size and more elastic deformation is stored in the sheet. Compared at equal penetration or shear zone length, instead of equal U_y , the changes in both forces and strain concentrations are less pronounced.

Clamping of both sheet strip ends and clamping of only one end creates different conditions in the plastic zone, as shown in figures 7 and 8. Due to the unsymmetrical boundary conditions with only one side clamped, the strain field is unsymmetrical and maximum strain is found at the unclamped side

Figure 7: Simulated plastic strain field with two clamps at U_y equal to 2.25 mm.

Figure 8: Simulated plastic strain field with one clamp at U_y equal to 2.25 mm.

around the shear tool radius. Also noticeable, is the small element distortion, possible through the adaptive remeshing used. With one clamp released, the y -directional force F_y decreases, but the free strip end will rotate around the z -axis as shown in figure 8 and apply additional x -directional force on the shear tool. Thus, F_x increases according to figure 9.

The friction coefficient in sheet metal to shear tools contact has large impact on forces. Especially F_x increases rapidly with increased friction coefficient, but at U_y around 2 mm, the conditions are reversed as shown in figure 10. When the initial clamp force is kept reasonably low, that is an order of magnitude lower

Figure 9: Force curves from the FE based perturbation analysis, showing the effects of clamping one side or both sides of the sheet.

than forces from the shearing, simulations indicate that effects of variations in friction coefficient in the sheet to clamp contact are small. At friction coefficients between 0.05 and 0.2 the effects on F_x and F_y are less than 1 %.

Increasing the tool radius increases F_x , especially at U_y between approximately 1 and 2 mm. Meantime, the results in figure 11 show that F_y is more insensitive to radius changes.

Changes in element size results in strain gradient changes close to the contact between sheet metal and shear tool radius. Small elements will resolve local gradients more accurate and predict higher strain concentrations. However, the resulting tool forces are insensitive to local strain gradient changes. Different element sizes can also change the sliding contact conditions around the tool radius, where large elements result in poorly rounded edges and possible mechanical locking. Here, the 90° shear edge radius is modeled with three elements, i.e. 30° per element. If r is the radius and α is the element angle then $r(1 - \cos(\alpha/2))$ will be the maximum radius penetration. Relative to the element side length $2r \sin(\alpha/2)$ the element penetration is 6 % at 30° element angle.

Although the 2D-models have a manageable (around 10^4) number of elements, the small explicit time step due to the proportions of element size and wave speed together with the shear process time, makes mass scaling necessary for feasible simulation run times. Adding nonphysical mass decreases the wave velocity and makes the simulation sensitive to transients. With moderate accelerations, the effects of mass scaling are negligible.

While F_y scales approximately proportional to sheet thickness, the effects on F_x are more complex. According to results in figure 12, F_x decreases with increased sheet thickness at large U_y .

Observations of changes to simulated forces when perturbations are introduced to the flow stress model at different regions along the plastic strain axis, determine the required range and accuracy of material input data. Figure 13

Figure 10: Force curves from the FE based perturbation analysis, showing influences of variations in friction coefficient. Four friction coefficients, 0.05, 0.10, 0.15 and 0.20 are shown and all arrows are pointing in direction of increased friction coefficient.

Figure 11: Force curves from the FE based perturbation analysis, showing the influences of shear tool radius variations. Four radii, 150 μm , 200 μm , 225 μm and 250 μm are shown and all arrows are pointing in direction of increased radius.

Figure 12: Force curves from the FE based perturbation analysis, showing influences of sheet thickness variations. Four sheet thicknesses are shown, the three closely spaced lines represents 4.9 mm, 5.0 mm and 5.1 mm and the fourth line represents 6.0 mm sheet thickness. All arrows are pointing in direction of increased sheet thickness.

shows the original Hollomon flow stress model along with the perturbed models where 50 MPa (6 % rise) is added to the flow stress over, respectively under, a plastic strain of 0.3. To avoid steps, the perturbations are added as $\sin^2$ -ramps over a 0.1 strain interval. The force curves in figure 14 show results from shear simulations and apparently, F_y is mostly dependent on small strain flow stress at small U_y and mostly dependent on large strain flow stress at large U_y .

4 Experimental set-up

Considering the perturbation analyses results, experimental set-up requirements are formulated to meet the performance criteria of distinguishing 1 % force changes obtained from change of an input parameter. Since a clearance change of one percentage point results in approximately 1 % change in forces, the target experimental clearance stability is an order of magnitude lower, i.e. the clearance should remain within 0.1 %. In absolute terms, that is 5 μm when shearing a 5 mm sheet. Likewise, analyses with perturbed shear tool radius suggests a target radius variation of a few micrometers.

Clearance stability and accuracy in force measurements are identified as weaknesses in industrial applications. In experimental set-ups, wise use of sliding guides can accomplish sufficient clearance stability, but guides are always associated with friction losses and will impinge the force measurements. With sliding guides disqualified, internal balancing of x -directional forces through symmetry, is the viable solution identified. Hence, a symmetric experimental set-up, figure 15, has been designed and built. The constructed symmetric set-up uses four shear tools, where forces are measured on the inner two and clearance is changed by means of shims behind the two outer. Analogies to blanking are seen if the outer shear tools are considered the die and the inner

Figure 13: Flow stress curves representing the original Hollomon model and perturbed models with 50 MPa added to the flow stress over respectively under 0.3 in plastic strain.

Figure 14: Force curves from the FE based perturbation analysis, showing effects of perturbations in the flow stress model. Along with the original Hollomon model are perturbations of 50 MPa applied at plastic strains over respectively under 0.3.

Figure 15: Schematic front view of the experimental set-up showing strain gauge positions as black squares. Sheet strips are clamped on both sides.

shear tools the punch. For simplicity, consider a rectangular punch and die configuration with a sheet strip across. Some stiffness and clearance stability are sacrificed when the two inner tools are separated by a strut that is inserted to allow measurement of F_x . However, F_x is important in shearing and of interest to measure. Further, F_y is measured in the pillars above respectively inner shear tool. All cross-section areas of the pillars and the strut are dimensioned as a compromise between safety against plasticity, high strain measurability and low elastic shortening of the strut. Based on the F_y to F_x ratio received in the perturbation analyses, iterative FE-simulations of the experimental set-up, figure 16, are used for positioning the tools relative to pillars and strut, so to avoid tool rotation due to pillar bending. Figure 16 shows the final position with corresponding stresses as result of applied loads F_x and F_y taken from respectively maximum value in figure 9.

Absence of external contacts in the elaborated experimental set-up, enables accurate measurement of forces without interfering friction, through strain gauge measurements on the pillars and the strut. Here, F_y is measured individually for the two symmetry sides, while F_x is equal by design. With large length to cross-section ratio for the pillars and the strut, linear cross-section stress distributions according to Saint-Venant's principle are ensured. Regarding the strut, high length to cross-section ratio is achieved through introduction of gaps, as shown in figures 15 and 16, resulting in four beam-like parts with equal and square cross-sections. The FE-simulation, shown in figure 16, confirms the assumption of linear stress distribution over the pillars and strut cross-sections, that is applied when the strain gauge measurements are used to calculate the mean normal strain. Slender pillars also imply that less force is absorbed by the pillars in cantilever mode, i.e. here less than 1 % of F_x .

Figure 16: Simulated x -directional stress (left) and y -directional stress (right) in the experimental set-up under applied loads F_x and F_y taken from maximum values in figure 9. Only half the symmetric set-up is simulated and both top and bottom plates are assumed to rest at rigid bodies. Fringe stress levels are in MPa.

At instrumented pillar cross-sections, three strain gauges are oriented for axial strain measurement and individually placed around the pillar circumference with 120° separation, as illustrated in figure 15. Quarter bridges and sampling to separate channels allow bending estimation in addition to mean normal strain measurement. Strain measurements on the strut are bending compensated through half bridge connection of the opposite facing gauges. Strain gauges with effective length of 5 mm, resistance of $119.6 \pm 0.4 \Omega$ and a gauge factor of $2.07 \pm 1\%$, are used throughout. Signal conditioning by means of an amplifier system operating at a fixed gain of 100 is applied to the bridge signals before anti-aliasing filtering and sampling at 600 Hz. In order to establish reference strain levels during the experiment, the technique of shunt calibration is used.

Figure 17 shows the Wheatstone bridge configurations. The quarter bridge voltage is $U = \frac{1}{4}U_{DC}\varepsilon g$, where U_{DC} is supply voltage, ε is strain and g is the gauge factor. Similarly, half bridge voltage is $U = \frac{1}{2}U_{DC}\varepsilon^N g$, where strain ε^N is the bending compensated normal strain. Axial pillar and strut strains are $\varepsilon_P = \frac{1}{3}\sum_{n=1}^3 \varepsilon_n$ and $\varepsilon_S = \frac{1}{4}\sum_{n=1}^4 \varepsilon_n^N$ respectively, where ε_n are strains from the three gauges around the pillar and ε_n^N are normal strains from each of the struts four quadratic cross-sections. Through use of relays, the shunt resistors R_S are connected simultaneously for all bridges and channels. Signal shunting is invoked short before and after each shear. Since the process of mounting and clamping the sheet strips takes time, strain levels are zeroed after fracture to decrease the effects of possible temperature drift.

Figure 17: Wheatstone bridges used in the strain gauge measurements. Half bridges are used for the strut and quarter bridges for the pillars.

Figure 18: Experimentally measured tool radius together with trend lines. What looks like a thick black line is a group of 40 measurements along the tool. The radius r is $220\text{ }\mu\text{m}$ and the measurements are spread over the interval Δr equal to $10\text{ }\mu\text{m}$.

Although the experimental set-up features stable clearance during the shear process, the present clearance change is optically tracked with a high speed camera and digital speckle correlation of the tools end surfaces. With a high resolution camera, the same method can measure surface deformations on the sheets xy -surface. Therefore, sheet visibility were considered in the experiment design. Here, a camera equipped with an 85 mm focal length and $1:1.8$ aperture objective is used to acquire images at 300 Hz with $120\text{ }\mu\text{s}$ exposure time.

Digital image correlation are applied to the captured high speed image data and gives a vector field of x - and y -directional displacement relative the initial position for each image frame. In order to obtain the shear edge position, first, the shear tool displacements are divided in tool mass center translation within the xy -plane and rotation around the z -axis. Then, under the assumptions of rigid tools and stationary outer tools, the displacements U_x and U_y at the tool radius, are given as functions of tool mass center translation and rotation.

Shear tools made of powder metallurgical cold work tool steel, are prepared with an edge radius and thereafter polished. The radius is verified through measurements with an optical profilometer and the result shown in figure 18 shows that the radius, $r \pm \Delta r/2$, is $220 \pm 5\text{ }\mu\text{m}$. During shearing, the tool surfaces are plentifully lubricated with grease, in order to achieve consistent and repeatable contact conditions.

5 Material characterization

In order to assess the robustness of the proposed experimental method, a comparison of experimental results to results from the FE model used during the design phase is considered. Therefore, proper material characterization of the intended sheet material is important.

Since shearing involves large strains, over an order of magnitude larger than obtained in tensile tests, calibration of the flow stress model against tensile test data would imply extrapolation and unreliability of simulated results already at small shear penetration depths. Therefore, uniaxial compression tests of cylindrical samples 4.5 mm in diameter and 8.0 mm long, processed from sheet in the x - and z -directions, constitute the material characterization. Simulations of the compression test procedure, show that force errors as result of barreling in the strain interval of interest, is less than 1 % when the sample is assumed to deform cylindrically. Thus, effects of barreling are neglected. The compression tests are assumed quasi static and the cemented carbide plate tools are lubricated with grease to assure low friction. Thorough centered and positioned samples are important to avoid skew compression and resulting inhomogeneous plasticity and underestimated stress. Once more, simulations are applied in order to obtain a tolerance on compression tool parallelity. With the criteria of less than 1 % force error, the maximum unparallelity of 0.5° is allowed and assured through measurements on the compressed samples. Figure 19 shows a schematic representation of the compression test set-up. In all tests, the compression velocity v_c equals 0.01 mm s^{-1} and the system force F_c is measured with a 100 kN load cell. In order to access the actual sample compression velocity and accumulated displacement, the machine stiffness k_c is measured and approximated linear for the entire load interval. The sample compression displacement was determined from the measured displacement u_{cm} as $u_c = u_{cm} - F_c/k_c$.

With least squares regression, the acquired compression test data for the selected hot rolled cold forming steel is used to fit Hollomon's material parameters. Best fit is achieved with the coefficient K equal to 923 MPa and the exponent n equal to 0.158, figure 20.

6 Experimental results

Analysis of the high speed image data from experiments, results in a displacement vector field as shown in figure 21. Further, the obtained clearance change U_x from shearing of a common steel grade sheet at different clearance and clamp configurations are shown in figure 22. Rotation of the inner shear tools is an effect of torque from variations in the force ratio F_y to F_x , as the forces are applied acentric. With force ratios close to those used in the experimental set-up design, the rotations are small. As the strut elastic length change is typically $2 \mu\text{m}$ during characteristic loading, U_x must be mostly mutual displacement of inner shear tools and strut relative the two outer, so that the clearance is redistributed between the symmetry sides. Any inequality between the symmetry sides that results in changed F_x , like mispositioned first contact or other geometrical or mechanical inequality, will trigger such displacement. Measurements shown in figure 22 indicate that an equilibrium position is found before U_y reaches 0.5 mm. During the shearing that remains, the clearance stays within

Figure 19: Schematic representation of the compression test set-up where the process is controlled by the velocity v_c and the system force F_c is measured with a load cell. Machine stiffness is labeled k_c .

Figure 20: Flow stress as function of plastic strain, obtained from compression test data with the assumptions of constant volume and cylindrical sample shape throughout the entire test, shown together with the fitted Hollomon function.

Figure 21: Images of the speckled shear tools with vector field overlay. Vector field in (a) shows total displacement while the mass-center displacement of respective tool is subtracted in (b). Vectors in (a) and (b) are scaled individually.

Figure 22: Experimentally measured clearance change U_x at the tool radius for different clearance and clamp configurations.

10 μm variation. According to simulations, sheet deformations at U_y less than 0.5 mm are mostly elastic, and thus the penetration is small and only half the tool radius have sheet contact.

All force measurements have signal to noise ratios around 100. Depending on the Wheatstone bridge configuration used, the peak-to-peak levels of the noise varies. Characteristic values are 0.6 kN for F_y and 0.3 kN for F_x .

As a final quality examination, experimental and simulated results are compared. Although the constant acceleration used in the perturbation analyses is anticipated to coincide rather well with the experimental conditions, the final validating simulations of experiments are governed by experimentally measured displacement as function of time. Figure 23 shows experimental and simulated

Figure 23: Comparison of experimental and simulated forces from shearing of a 5 mm thick sheet strip. Experimentally, fracture occurs at U_y less than half the sheet thickness, i.e. at the experimental curve end.

force curves from shearing a 5 mm thick sheet strip with one side unclamped and 0.64 mm, i.e. 13 % clearance. Except for a small deviation of simulated forces at large U_y , forces from experiment and simulation coincide fairly. After fracture that occurs at the experimental force curves end, all load carrying abilities are lost and the forces drop to zero.

7 Discussion

Typically, the force displacement curves from shear simulations show an initially linear force rise when the sheet deformation is mostly elastic with small plastic deformations close to the tool radius. Next, comes a gradual level out of forces when plastic zones grow inwards from both tools and form a continuous plastic shear zone through the sheet. After the formation of a throughout plastic shear zone, the force curve shapes are largely dependent on material hardening and shear zone size.

During the experimental shearing, clearance changes have the same order of magnitude as requested in the design phase. The initial clearance changes associated with small penetrations are tolerable and easily measured with the applied optical method. Moreover, the signal to noise ratio in force measurements is above 100 without shielding of electronics. One vagueness in the clearance measurements is the assumption of rigid tools when the shear edge position is calculated from the vector field. Elastic tool deformations as result of F_x and F_y are not considered in the calculations. This source to clearance change depends on the F_y to F_x force ratio and according to simulations, the tools deform such that clearance is decreased with a few micrometers during load.

While all the perturbation analysis simulations are displacement controlled through constant tool acceleration, the final verifying simulations are governed by corresponding experimentally measured U_y . Experimentally, the process in the hydraulic press, with elasticity in structure and fluid, is not controlled by displacement, but rather some combination of displacement and force.

Even though the experimental set-up is well defined, uncertainties still remain in contacts and bulk material property variations. Establishment of the sheet to tool contacts is associated with a nonlinear response when the stiffness gradually approaches Young’s modulus. Further, the friction coefficients in all contacts are unknown and, as concluded in the perturbation analysis, the shear process is sensitive to friction.

When simulating more ductile materials, penetration before fracture increases and results in increased element distortion and further need for remeshing. The applied adaptive remeshing introduces transfer errors, originating from lost element peak stress during interpolation and remapping to the new mesh (Torigaki and Kikuchi, 1992), and shown as dips in the force curves and also relaxation in the stress field. However, according to simulations with remeshing at smaller penetrations, the resulting tool forces are believed to recover in about one third of the remeshing interval and errors are considered smaller than numerical errors from distorted elements.

8 Conclusions

Based on the performed perturbation analyses and validating experiments, some conclusions about the developed experiment, and shearing in general, can be made:

- Clearance and clamping configuration are identified as two important cutting parameters with large impact on forces. Also the friction coefficient in sheet to tool contact is important and primarily impacts the x -directional force F_x , i.e. striving to separate the tools.
- Clearance stability is obtained through symmetry and balancing of forces. Further, optical tracking of the shear tools confirms that the clearance stays within 10 μm during load, i.e. 1–2 % of the initial clearance.
- Tool forces decomposed in two directions, are measured without external friction losses with signal to noise ratios in the order of 100.
- The experimental shear procedure fulfills the initially stated demands to allow detection of 1 % force changes as result of changes in the studied input parameters.

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