Investigation of Material Flow During Linear Flow Splitting Using Tracer Diffusion Experiments and Finite-Element Simulations

Laura Ahmels, Daniel Dehtyriov, Enrico Bruder,* and Andrey Molotnikov*

The deformation behavior and evolution of strain distributions of flat metal sheets subjected to the high-strain forming process of linear flow splitting (LFS) are studied using experimental and numerical techniques. The new tracer gradient method for the mapping of material flow based on diffusional concentration gradients is proposed. The method is validated using theoretical predictions for rolling of a sheet and shown to overcome the limitations of previous techniques. A parametric finite-element model for LFS of a HC800LA grade steel is developed and validated against the results of the tracer gradient method. A sensitivity study is undertaken to investigate the effects of strain-hardening behavior and sheet thicknesses on the LFS process. A good agreement between experimental and numerical results is obtained, with the friction between rolls and sheet found to be a critical parameter in the modeling of the process. It is further observed that the formation of the characteristic steady state in the LFS process is linked to the material-hardening behavior and not the geometry of the sheet.

1. Introduction

Profiles with bifurcated cross sections offer great potential to increase the stiffness-to-weight ratio of components, which makes them a key element of modern lightweight design. The production of these branched structures often requires the joining of parts, which creates potential weak spots within the structure. Linear flow splitting (LFS) is an innovative forming process that allows for the integral production of bifurcated structures without joining operations, avoiding the creation of possible weaknesses. During this incremental process, two obtuse-angled splitting rolls are driven stepwise into the edges of a sheet metal, whereas two cylindrical supporting rolls prevent buckling (Figure 1). For a more detailed discussion of the process and its innovation potential, the reader is referred to a recent overview.[1] It has been shown that the setup of splitting and supporting rolls leads to the formation of a hydrostatic compressive stress state in the forming zone, which increases the formability of the material and thereby prevents cracking during the high-strain process.[2]

A survey on the properties of flow split material from different steel grades demonstrates that the high strains at the split surface of the flanges result in an increase in hardness of more than 100% across all investigated grades, which renders the split surface very suitable for rolling contacts such as in linear guides,[3] which was also proven experimentally.[4] The LFS process results in a characteristic local property distribution in the profiles after a few splitting steps, which is shown in Figure 2. Perpendicular to the flange surface, there is a steep gradient in hardness and grain size.[5] Highly elongated ultrafine grains with high hardness are observed near the split surface, whereas a cold worked microstructure exhibiting lower hardness values, i.e., only a moderate increase to the as-received condition, is observed toward the lower surface. Parallel to the flange surface, however, both the microstructural properties and hardness are constant, with the exception of regions near the flange tips.[2] It should be noted that further splitting steps do not alter the hardness at the flange surface and the gradient perpendicular to the split surface remains unchanged. The LFS process changes the geometry of the profile and leads to the formation of a steady state as well as the ultrafine-grained microstructure. Therefore, the LFS process can be regarded as a hybrid, which combines severe plastic deformation (SPD) process and conventional forming process. The LFS process also shows some similarity to large strain extrusion machining (LSEM) process[6] and the plastic flow machining (PFM).[7] In both cases, the geometrical confinement...
of the material flow leads to large deformation in a thin layer and produces gradient microstructure which varies from conventional to ultrafine grained.

The SPD-related features of the process are the main reasons for the exceptional increase in strength and can lead to a novel design of lightweight structures. However, the local increase in strength and hardness can only be exploited in the product design if the evolution of the mechanical properties can be predicted using numerical methods. For conventional forming processes, this is usually done using finite-element (FE) methods. However, the material-specific features of an SPD process might not be describable by conventional flow curve approaches, which are typically used in the simulations. For instance, the microstructure produced by an SPD process stops affecting the hardening behavior of a material after a certain degree of deformation, which goes beyond the scope of conventional hardening models that mainly cover stage III hardening. In fact, earlier work indicates that conventional cold working behavior is insufficient to describe the LSF process with its very high strains that evolve in the flanges. A possible explanation is that grain boundary migration carries significant parts of the severe deformation. Another mechanism could be the formation of shear localizations that has been observed in ultrafine-grained Fe. In contrast to the hardening behavior in other SPD processes such as high-pressure torsion, this effect can also not be understood in terms of a saturation in grain size and corresponding flow stress. Unlike the other SPD processes, where only the areas with the finest microstructure do not undergo changes upon further straining, the microstructural properties of the coarse-grained regions in the LFS profiles also remain invariant during additional straining. Another surprising fact is the similarity of the microstructural and hardness gradients found in LFS profiles of different steel grades despite their strongly differing hardening behaviors in the conventional regime, i.e., at low-to-moderate strains. It indicates that the material behavior, including hardening and flow path, becomes invariant to the yield strength of the initial material and the strain-hardening behavior in the conventional regime.

The determination of flow curves at high strains, however, is challenging. Common approaches such as compression tests, severe rolling, or severe torsion are not feasible for sheet materials due to their geometric restrictions. Therefore, the validation of a numerical simulation of the LFS process attempted in this work requires a different approach. Previous numerical studies on the LFS process were mostly using the splitting force to validate the models. Another approach is to use the resultant geometry of the profile. However, a robust numerical model validated against the strain distribution within the profile is necessary to accurately reflect the physics of the process. The complexity of process geometry, resultant strain distribution, and material flow in the LFS process requires the development of new methodology to study and understand the material flow during LFS. Existing methods such as marker insertion techniques are based on the introduction of significant amounts of foreign material, potentially affecting and altering the material flow. Other established techniques such as the analysis of surface grids or speckles only work at lower strains and with moderate friction between tool and work piece. Hence, the limitations of the aforementioned methods call for the development of a novel approach to the mapping of material flow at high strains.

Figure 1. Principles of LFS showing the setup of the rolls (left), incremental stages and splitting of the sheet (middle), and the final shape of the work piece (right).

Figure 2. Local gradient microstructure distribution of linear flow split profiles showing elongated pancake-like grain morphology in the top flange region of a sample, which transitions to coarser equiaxed grains toward the center of the sample.
In this work, a method which relies on elemental tracers is proposed. Before deformation, the work piece is coated with an element with similar atomic radius to the base material and is subjected to subsequent annealing. This element acts as a tracer and the diffusion enhanced by the annealing causes the formation of a concentration gradient in the region of the work piece adjacent to the layer. The sample is then subjected to the deformation process. The changes in the gradient caused by deformation can then be related to the principal strain imposed on the material perpendicular to the surface. Due to the fact that the tracer gradient method is insensitive to certain strain modes such as shear, this method will be tested on a forming process with a simple and well-known strain state, cold rolling, before being used to analyze the LFS process and validate its simulation. The geometry and kinematics of the numerical study are identical to the experimental work, and a parametric sensitivity study is undertaken to determine the relevant input parameters. The resultant novel validated model is used to better understand the material flow and formation of surface strain gradients in the LFS process.

2. Experimental Section

2.1. Validation of Tracer Gradient Method: Cold Rolling of Steel Sheets

Steel strips (125 × 15 × 2 mm³) of grade H480LA were polished and electroplated with Ni using pulsed deposition, resulting in a Ni layer with a thickness of 25 μm. After undergoing heat treatment at 700 °C for 10 h under Argon atmosphere, the electroplated sheets were incrementally cold rolled to different thicknesses with a constant reduction of 0.2 mm per step. To prevent roughening of the Ni-plated surface at high rolling reductions, two steel strips were spot welded on each other with their Ni layer on the inner sides before rolling. The Ni gradient in the rolled samples as well as in a reference sample were characterized using energy-dispersive X-ray spectroscopy (EDX). Five EDX line scans were conducted on polished cross sections of each steel strip (for details, see section EDX Analysis).

2.2. Determination of Material Flow During LFS

A coil from HC800LA grade steel with a thickness of 1.5 mm and a width of 88 mm was cut into samples of 250 mm in length. The band edges were electroplated with a Ni layer with a thickness of 25 μm. The parts were then subjected to the same heat treatment as the previous samples for rolling (700 °C, 10 h). The produced gradient was analyzed using EDX (for details, see section EDX Analysis). The parts were then welded into the coil and subjected to LFS up to a maximum of seven steps. After each step, one sample was taken for analysis, and the gradients in the splitting center and at distances of 0.5 and 1 mm to the splitting center were analyzed using EDX.

2.3. EDX Analysis

EDX measurements were carried out on all samples as line scans perpendicular to the Ni/steel interface with a step size of 0.1 μm. The acceleration voltage was chosen to be 20 kV for the samples subjected to cold rolling or to up to four splitting steps to receive a smooth gradient and 8 kV for the more severely deformed samples to increase the resolution to accommodate the decreasing gradient width.

To incorporate the broadening of the gradient due to limitations in resolution of the EDX method, reference measurements (8 kV as well as 20 kV acceleration voltage) were carried out on an electroplated sample not subjected to any heat treatment. By deconvoluting a perfect step profile from the measured gradient using the Total Variation L2-method,[11] the broadening of the signal was calculated. The obtained signal broadening curves were used to deconvolute the gradients measured in the samples subjected to heat treatment and subsequent deformation. The gradient depth (i.e., the distance between the two Ni intensity plateaus in the steel and the Ni layer, see Figure 3) was then estimated from the deconvoluted curves.

After determining the gradient depth t₀ of a heat-treated nondeformed sample, the average true strain εtrue and the rolling reduction R of a sample with the gradient depth t can then be calculated.

\[ \epsilon_{\text{true}} = \ln \left( \frac{t}{t_0} \right) \]  

\[ R = \frac{t_0 - t}{t_0} \]

For each data point, five EDX measurements were carried out and their resulting gradient depths were averaged.

2.4. Numerical Simulation of LFS Process

An elastic–plastic FE simulation of the LFS process was conducted to characterize the strain gradient perpendicular to the splitting surface as well as visualize the material flow. FE simulation will also provide a critical insight into the evolution and stationarity of the characteristic property distributions. The
numerical simulation of the LFS process was conducted using the QFormVX package. This package is specifically designed to simulate metal-forming operations and offers automatic remeshing alongside point and flow-line tracking with forward time integration.

The simulation of the LFS process was set up as a 2D plane strain general forming problem, which is a simplification to the real 3D process. However, experimental investigations such as texture analyses and measurements of the profile elongation indicate that the plane strain assumption is a reasonable approximation due to the comparatively low strains in feed direction. The process was modeled as an incremental forming process, with reference to the coordinate system shown in Figure 1. Each increment involved raising the splitting roll by $y_{inc} = 1$ mm in the normal direction (ND) and raising the work piece such that the splitting center was in contact with the lowest point of the splitting roll, followed by the deformation step, where the splitting roll was lowered, $y_{inc}$ at a constant velocity of $y_{inc}/10 = 0.1$ mm s$^{-1}$. After simulation of each pass, the deformation history was passed on to the subsequent simulation. To reduce the computational time, a symmetry condition was used such that only one splitting roll and half of the sheet were modeled. To validate the numerical model against potential sensitivity to small asymmetric perturbations about the half-web plane, the entire width of the sheet was simulated.

The supporting and splitting rolls were treated as nondeformable rigid bodies. For the metal sheet, two different strain-hardening curves based on experimental compression and tension tests were used as inputs to the simulation, see Figure 4. The density, Young’s modulus, and Poisson’s ratio were assumed to be both homogenous and constant throughout the process. The two flow curves used in the simulation were utilized to investigate the influence of different hardening behaviors on the material flow. As very high strains were expected during the LFS process, the experimentally obtained flow curves had to be extrapolated toward higher strains. Flow curve one in Figure 4 was based on mild, unalloyed steel DD11 compression experiments for lower strains and extrapolated using the equation proposed by Hollomon, whereas flow curve two was based on tensile tests on heat-treated HC800LA (700 °C, 10 h), extrapolated with a constant strain-hardening rate (stage IV hardening).

To track both the material flow and properties in the splitting region, tracking points were seeded at the band edge every 5 μm both parallel and perpendicular to the edge to a depth of 50 μm, as shown in Figure 5. The tracking points were necessary to compare the simulation results with the tracer gradient profiles, which are insensitive to certain strain modes and thus do not predict total equivalent strains but only principal strains perpendicular to the surface. Flow lines spaced at 50 μm apart perpendicular to the band edge were used to visualize regions of material flow and compression. A highly refined grid is necessary to accurately resolve the distances between tracking points, and a grid density gradient was imposed such that there were a minimum of five linear first-order tetrahedral elements between any given tracking point. As the sheet was deformed in time, the mesh was regenerated at every time step and all values interpolated to new nodes. Likewise, both the splitting roll and supporting cylinders were meshed such that the surface nodes were no larger than 2.5 μm apart, ensuring accurate modeling of the contact physics.

The location and solution at the tracer points were read out at each integrable time step, with the tracer points being used to compare the experimentally measured tracer gradient to the simulation. This was achieved by assigning the points with tracer concentration. The tracer concentration of each point was calculated based on the distance to the surface using the complementary error function fit of the measured initial gradient. The new position of these tracer points in combination with their tracer concentration at a certain flange length was used to determine the predicted tracer gradients of the simulations. Similar to the experimental tracer gradient, which is based on several neighboring line measurements, the numerically predicted tracer gradient at a given position was calculated using all tracer points within a distance of $+/−200$ μm in rolling direction.

Matching the contact conditions is key to matching experimental results for validation, with the friction between
splitting roll and sheet found to strongly influence the solution (see Section 3).

The friction between sheet and splitting roll was modeled using the Levanov model given as

$$\tau = f k \left(1 - \exp\left(-b_0 \frac{\sigma_n}{\sigma_s}\right)\right)$$

(3)

Here, $b_0 = 1.25$ is the Levanov coefficient and $\tau$ is the specific friction force, $f$ is the friction factor, $\sigma_n$ is the normal contact stress, $\sigma_s$ is the material flow stress, and $k$ is the maximum shear stress determined by the material flow stress of flow curve 1 as $k = \sigma_s / \sqrt{3}$. To determine the appropriate friction factor $f$, the shear strain distribution normal to the surface of the flange was compared with experimental observations of shear texture component distribution. The parameter $f$ was iterated until the convergence to the experimental solution was obtained. Furthermore, the sensitivity of the solution to changes in the friction factor was explored.

After determination of a suitable friction coefficient, the sensitivity of the solution to both changes in the sheet geometry and sheet material was investigated. This was done by changing the flow curve from flow curve 1 to flow curve 2 (see Figure 4) and reducing the sheet thickness from 2 to 1.5 mm. The four combinations of parameters were referred to as A1, A2, B1, and B2 and are shown in Table 1. These models were simulated to a minimum flange width of 8 mm for comparison with experiments and model A1 to 16 mm for visualization of the formation of the steady state.

3. Results

3.1. Validation of Tracer Gradient Method: Cold Rolling of Steel Sheets

The tracer gradient method was verified using rolling of nickel plated sheets and comparing the experiential results to calculated theoretical values. Figure 6 shows the macroscopic rolling reduction of the sheet and the calculated rolling reduction based on the tracer gradient depth. It is shown that the data points measured by EDX match the theoretical prediction and follow a linear trend. Due to the fact that the local chemical composition changes within the tracer gradient, an impact on the mechanical properties is inevitable, which can affect the results to a certain degree. To assess the influence on the mechanical properties, the hardness distribution over the gradient depth was measured using a small-angle section. The results show an increase from 165 HV0.05 in the base material up to 174 HV0.05 with increasing Ni concentration. Therefore, it can be concluded that the tracer gradient method can be an effective tool to trace plastic strains under the given conditions. In addition, it was shown that nickel has only a limited influence on the mechanical properties of the steel, which makes it a suitable tracer element for mapping plastic flow in steel using EDX as the characterization method for the gradients.

3.2. Determination of Material Flow during LFS

In Figure 7, the measured Ni signals over depth show a decrease in Nl signal from the Ni layer at the flange surface toward the lower surface. The width of these gradients decreases with increasing number of splitting steps, indicating that the material is subjected to a compressive strain at each splitting step. The decrease is more pronounced between the splitting steps 1 and 2 than between steps 4 and 5.

The inhomogeneous slope of the gradients of early splitting steps is most likely caused by the initial diffusion gradient that is not homogeneous due to the influence of microstructural
features such as grain boundaries on the local diffusivity. At later splitting stages, the gradient is smoothed by the limited lateral resolution of the EDX analysis.

To estimate the amount of deformation occurring in different parts of the samples, the depths (see Figure 3 for definition) of the deconvoluted Ni gradient curves measured at different places in the samples are shown in Figure 8. Solid symbols indicate the usage of 20 kV voltage in the EDX measurements, open symbol data points were obtained using 8 kV acceleration voltage. As mentioned earlier, the depths of the deconvoluted Ni gradients at a distance of 0.5 mm from the splitting center show a decrease in the number of splitting steps, as shown Figure 7. At step 5, the curve levels off at a value of 0.7 μm corresponding to a true strain of 3.5, which is calculated using Equation (1).

The gradients measured at the splitting center match these values very closely, whereas the gradients measured at 1 mm distance to the splitting center exhibit larger depths up to step 5. After step 5, the values found at a distance of 1 mm approach the values found at the splitting center as well as in 0.5 mm distance. It should be noted that the value of 1 mm distance at step 1 could not be displayed as the flange length at this step is below 1 mm.

### 3.3. Numerical Simulation Results

To determine a suitable friction coefficient \( f \), the shear strain distribution close to the flange surface in model A1 with different friction coefficients is investigated (Figure 9). All curves show a maximum at or close to the flange surface and a decrease in shear strain toward higher depths where the strain levels off. A friction coefficient of zero corresponds to a shear strain of close to zero near the splitting surface, with the zero “cross-over” located at higher distances to the surface with increasing friction coefficient. It has been reported that shear texture components can be found close to the upper-flange surface up to a depth 20–25 μm, which coincides with the curve of \( f = 0.2 \).[14] Therefore, a friction coefficient of \( f = 0.2 \) was selected for all further simulations.

After the determination of a suitable friction coefficient for the numerical model, both the strain distribution and material flow are investigated as a function of time. Of interest in the LFS process is the material flow at the splitting edge, shown by flow lines in Figure 10. The initial distribution of flow lines is regularly spaced and both the bending and distances between flow lines give indication to how the material flows throughout the LFS process. At an incremental splitting depth of 2 mm, the flow lines in the vicinity of the splitting edge compress toward the splitting roll and “stretch” outward as more material is driven toward the splitting roll. By a splitting depth of 3 mm, a region of highly dense flow lines develops, within which large plastic strains are computed. As the LFS process is integrated forward in time, this region of high-flow-line density continuously expands outward, corresponding to a large region of high-strain gradients, with the exception of the flange tips. The near-surface tracking points compress toward and flow parallel to the splitting roll throughout the process, with the points furthest from the center of the sheet flowing significantly further than those within the process zone. The numerical model predicts the formation of a dead-zone at the splitting center as the points in the vicinity of the splitting center do not flow far from their initial positions.

The evolution in plastic strain for the selected studies is shown in Figure 11 and Figure 12. During the splitting, the plastic strain within the web as well as the flange tip remains below ≈0.5 up to a flange width of 16 mm. Apart from these areas, the plastic strain accumulates to values of around 2.0. Very close to the flange surface, a high-strain layer with plastic strains of 4 and above evolves, resulting in large strain gradients perpendicular to the flange surface. The formation of the large strain gradient at the surface of the sheet, and the overall strain distribution, is independent of the material thickness or material properties, which is in line with earlier experimental observations.[10] As a
measured for the thickness of the high-strain layer, the distance from the flange surface where the strain drops below 4 is shown as a function of flange width in Figure 13.

For Model A1 at large flange widths, the distance to a plastic strain of 4.0 exhibits a minor decrease in the order of 1 μm from a flange width of 8.5 mm to a flange width of about 12 mm, as is shown in Figure 13a. For flange widths greater than 14 mm, the curve converges to a value of around 23 μm.

A similar trend is shown in Figure 13b for the models B1 and B2. For both models, the thickness of the high-strain layer...
marginally decreases with increasing flange width and begins to converge at higher widths. However, Model B1 converges to a higher value of about 12 μm, as compared with 5 μm for Model B2. Furthermore, it is shown that Model B1 converges at a faster rate relative to Model B2, as shown in Figure 13b. When the distance between the splitting roll is compared for Model A1 and B1, which use identical hardening curves, but start with different sheet thicknesses, it is observed that the distance to the splitting roll is higher for Model A1 as compared with Model B1, as shown in Figure 13. This is a direct result of the larger dead-zone that forms in the thicker sheet. The dead-zones act to shift the plastic strain gradient from the surface of the flange to the boundaries of these dead-zones. Within the forming zone where the measurements are taken, the larger dead-zone of Model A1 hence increases the distance to a plastic strain of 4.0 relative to Model B1.

In contrast to these findings, the maximum plastic strain found in the first four splitting increments shows no convergence but rather follows a steady slope with increasing flange width, as shown for all models in Figure 14. The maximum plastic strain only shows minor differences between models using the same sheet thickness, i.e., A1 and A2 as well as between B1 and B2. The same is true for the resulting flange widths; the deviations of the points based on the same sheet thickness are also negligible. Therefore, the influence of the material-hardening behavior on both the flange width and maximum strain is small. However, the sheet thickness has a stronger influence on both the flange width and the maximum plastic strain. The increase in flange width within the first four splitting steps (the last data point of each curve in Figure 14) is lower for the models with smaller initial sheet thicknesses, i.e., B1 and B2. This is to be expected as less material is being fed toward the splitting roll. Second, the maximum plastic strain is markedly lower for thinner sheets, and the rate of change in plastic strain with splitting depth is lower than that of the thicker sheets.

4. Discussion

4.1. Comparison of Simulation and Tracer Method

The gradient depths measured at a distance of 0.5 mm from the splitting center are compared with the gradient depths predicted by simulations with both flow curves at the corresponding flange widths in Figure 15. Due to the fact that the real tooling system has finite stiffness, the flange lengths obtained in simulations with the same incremental step depth are higher than the experimentally determined ones. Therefore, the comparison between simulation and experiment is conducted over comparable flange widths instead of a comparable number of splitting steps.

It can be seen that the differences in predicted values due to different hardening curves are negligible and that they are in good agreement with the measured values, as shown in
Figure 15. Comparison of simulated and measured gradient depths in 0.5 mm distance to splitting center showing good agreement.

Figure 15. A more pronounced difference between simulations and experiment is observed at the lowest flange length, i.e., the first experimental splitting step. This can be attributed to the fact that the experimental tooling system shows elastic compliance, resulting in slight uncertainties in the alignment of the tooling system to the sheet metal in the experiment, especially in the beginning of the process. Slight misalignments at this stage will result in lower compression of the material than in the “ideal,” i.e., the simulated case. The fairly good agreement of all other experimental values with the simulation results shows that the simulation is capable of accurately capturing the deformation process at the early splitting steps that were experimentally assessed. It is also clear from the comparison of the simulated gradient depths with differing flow curves that the material flow at these earlier stages of the process is not sensitive to the material-hardening behavior within limits of this work. That is, the differences between the strain-hardening curves and resulting strain gradients are too weak to change the material flow substantially.

A significant difference between simulation and experiment is found in the values at the splitting center. While the experiment shows the same behavior at the splitting center and at a radial distance of 0.5 mm from it (Figure 8), all simulations predict the formation of a dead-zone in the splitting center. This region experiences significantly lower strains than other regions near the flange surface. The underlying reason for this discrepancy is linked to the alignment of the tooling system and the sheet. In the splitting process, slight differences in the first point of contact will smooth out the strain distribution, reducing the potential formation of a dead-zone.

4.2. Formation of a Steady State

An important aspect of the splitting process is the formation of the steady state after a certain number of splitting steps. For other processes with somewhat similar kinematics and strain gradients such as PFM, fresh material is brought into the surface via shear deformation, which limits the maximum strain and promotes a stable strain gradient. However, for LFS, it is shown in Figure 14 that the simulation results do not show convergence to a steady state as the maximum strain steadily increases with the number of splitting steps instead of approaching saturation. This difference can be explained by considering the plastic deformation behavior of the material close to the flange surface. In this area, the material is subjected to very high strains and its deformation behavior cannot be captured by conventional flow curves used in the simulations. In literature, different mechanisms have been presented that allow plastic deformation at high strains without significant strain hardening or grain refinement. It was demonstrated that grain boundary migration allows for the formation of a steady state during cold rolling of high pressure torsion (HPT)-processed copper. Dynamic recovery processes were reported to be the cause of the vanishing strain-hardening rate in equal-channel angular pressing (ECAP)-produced ultrafine grained aluminum. In ECAP-processed copper and nickel, grain boundary sliding has been shown to occur under tensile loading.

Following this hypothesis, only the distributions of strains below a certain threshold value have to be constant, as above this value no significant hardening or grain refinement occurs. This is due to the fact that dislocation interaction in grain interiors stops being a relevant hardening mechanism. For titanium processed by ECAP, it has been reported that the strain hardening is negligible after a strain of \(\approx 4.0\). The contour levels in Figure 11 and Figure 12 reflect this observation, with strain hardening anticipated to be negligible within the red high-strain regions. Consequently, whether new material is transported into the surface such as in similar shear-based processes or not as in LFS appears to be irrelevant for the evolution of a stationary property gradient.

The distance from the flange surface to this strain limit of 4.0 shown in Figure 13 indicates convergent behavior, suggesting that the strain state in the forming zone approaches a steady-state condition, even though the maximum strain still increases (see Figure 14). The strain distribution at a flange length of 16 mm (Figure 12) illustrates this steady-state region in the process zone, after which the properties of the developing flange remain homogenous in time.

At first sight, the assumption of no further grain refinement and hardening after a strain of 4 seems to contradict the observation of a microstructural gradient. However, a statistically sound experimental characterization of the microstructural gradient is only feasible in distances of 20 µm or more to the flange surface. As Model A1 (exhibiting the highest distance) predicts the occurrence of strains of 4 and higher only in depth of 20 µm or lower, it does not contradict experimental findings.

Comparing the converging behavior of the models B1 and B2, that are based on a differing material behavior with varying strain hardening (see Figure 4), it is clear that the model with lower strain hardening converges to steady state at a faster rate, implying that the formation of the steady state is closely linked to the strain-hardening behavior at high strains. The constant hardening rate in flow curve 2 (Figure 4) up to high strains seems to delay the evolution of a steady state. In fact, a linear-hardening behavior might even prohibit the formation of a real steady state, considering that it has been shown that a steady state in HPT processing is only possible with a power law-type hardening behavior.
In contrast to this, the maximum strain within the profiles (Figure 12) only shows slight differences between models A1 and A2 as well as B1 and B2 that are based on differing hardening curves but strong differences between A1 and B1 as well as A2 and B2 representing differing sheet thicknesses. This allows the conclusion that the maximum strain is linked to geometrical features, whereas the steady-state formation is primarily influenced by the material behavior.

5. Conclusion

In this work, the tracer gradient method and numerical simulations were used to study the material flow in the LFS process. The main conclusions of this work can be summarized as follows. 1) The tracer gradient method was demonstrated to be suitable to access material flow at high strains in the LFS process. The experimental values are in good agreement with simulations based on both flow curves in the early splitting stages. 2) It was shown that the friction between splitting roll and sheet has a major influence on the strain distribution close to the surface with the estimated friction value based on experimentally observed shear texture distributions, leading to a quantitatively correct strain distribution near the surface in the early splitting stages. 3) For the later stages of the splitting process, where no experimental data for quantitative validation were available, the simulations based on both flow curves, while exhibiting different values, were able to qualitatively predict the characteristics of the LFS process, i.e., the strain distribution as well as the formation of the steady state. Therefore, it can be concluded that continuum mechanics simulations can be used for qualitative prediction of the property distribution in linear flow split profiles. 4) The comparison of the simulation results based on both flow curves shows that the formation of the steady state is caused by the diminishing strain hardening of the material, i.e., strongly depends on the flow curve. Hence, quantitative predictions of the property distribution in linear flow split profiles remain challenging for continuum-based simulations. This is an agreement with previously reported results showing that the extrapolation of a conventional flow curve up to high strains falls short to predict the increase in yield strength close to the flange surface by 100 MPa.[1]

Overall, it can be concluded that while qualitative predictions are robust toward the flow curve, quantitative predictions heavily rely on the knowledge of the flow curve at very high strains that are challenging to obtain, especially for sheet material.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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