Integral sheet metal design – state of the art and future challenges

E Bruder, V Kaune and C Müller
Physical Metallurgy Division, Technische Universität Darmstadt,
Alarich-Weiss-Str. 2, 64287 Darmstadt, Germany
E-mail: e.bruder@phm.tu-darmstadt.de

Abstract. The innovative forming processes Linear Flow Splitting (LFS) and Linear Bend Splitting (LBS) were developed to facilitate the continuous production of branched profiles with tailored sheet thickness by inducing severe plastic strain. In contrast to most SPD processes the stress state in LFS and LBS is very complex and plastic deformation is confined to limited volumes which results in steep strain gradients and consequently ultrafine grained (UFG) gradient microstructures. Even though the processes have been commercialized, the increased lightweight potential that originates from the local grain refinement remains mostly idle since it is neither fully understood nor easily assessable yet.

The present work shows the state of the art for the LFS and LBS processes and compares the microstructures and distribution of mechanical properties for different steels processed with different LFS parameters. The data is used to identify characteristic manufacturing induced properties that are insensitive to processing parameters. Based on the experimental results a material flow model for the processing zone is proposed which is discussed with respect to the current understanding of plasticity at severe strains.

Keywords: Surface Severe Plastic Deformation, Work Hardening, Linear Flow Splitting, Linear Bend Splitting, Gradient Microstructures

1. Introduction
The use of Severe Plastic Deformation (SPD) as top down approach to refine microstructures of metals and alloys to the submicron range has been investigated extensively during the last decades [1-3]. Aside from the scientific interest in fundamental research on plasticity phenomena at large strains, there is also a strong technological interest in these processes which is driven by the exceptional mechanical properties that are associated with the presence of ultrafine grained (UFG) microstructures [1]. Even though high strength materials are needed for a wide range of commercial applications where lightweight design is mandatory, the commercial success of SPD processes is rather limited so far [4]. The main reason for this are most likely the high processing costs of the predominantly discontinuous SPD processes but there is also a strong competition from materials based on modern alloy design and thermo-mechanical processing [5]. However, the Linear Flow Splitting (LFS) and Linear Bend Splitting (LBS) processes that are reviewed in the present paper demonstrate that UFG microstructures by SPD and commercial success in mass markets are no antagonisms.

The LFS and LBS processes also referred to as split profiling and split bending have an exceptional position in the field of SPD. In contrast to conventional SPD processes their primary objective is not the generation of UFG microstructures while retaining the initial shape of the workpiece but the production of branched profiles from plain sheet metal [6-8]. However, since LFS and LBS induce severe strains under high hydrostatic compressive stresses they generate UFG microstructures by the same mechanisms [9]. Due to the fact that the deformation is confined to a small volume which exhibits steep strain gradients and maximum strain levels at the surface, LFS and LBS are rather Surface Severe Plastic Deformation (S²PD) processes such as surface mechanical grinding [10], or gradation rolling [11] than bulk SPD processes like equal-channel angular extrusion [12].
1.1 Linear Flow Splitting (LFS)
LFS is an incremental forming process used to transform plane sheets into integral single or double Y-beams by massive forming at ambient temperature. The tooling system is a modified roll forming stage which consists of two cylindrical supporting rolls and one or two obtuse angled splitting rolls for single or double sided LFS, respectively (Fig. 1). The main functions of the supporting rolls are the transportation of the sheet through the stage and the stabilization in sheet normal direction to prevent buckling. In the first stage of the process the splitting roll drives into the band edge by an incremental splitting depth $y_{inc}$, thereby forcing the material to flow parallel to the surface of the splitting roll (Fig. 1 (right)). During subsequent steps the splitting roll drives further into the sheet whereas the width of the supporting rolls is reduced so that the thickness of the flanges is kept constant. [6, 7, 9, 13]

![Process principle (left, center) and geometrical characteristics (right) of LFS][13].

It should be noted that the axes of the splitting rolls and the supporting rolls don’t have to be in-plane but can have a certain offset. It was shown that a certain offset is very beneficial for the process as this leads to a stronger overlap of the strain fields from the splitting and supporting rolls, which increases the hydrostatic compressive stresses in the processing zone and in consequence also the formability [13]. Texture analysis across the thickness of the flanges carried out on HSLA steel profiles show a very strong bcc rolling texture near the split surface and shear components at the lower side of the flanges [14]. This is plausible with respect to the absence of cracks which results in an enormous surface enlargement by a nearly uniaxial material flow at the split surface. The presence of shear components at the lower side of the flanges is likewise comprehensible considering that the material flow around the radius of the supporting rolls (see Fig. 1) has some similarities with continuous confined strip shearing [15].

A key aspect of LFS is that the deformation is restricted to the band edges of the sheet. Therefore, the complexity of profile geometries is limited to single or double Y-beams. While subsequent roll forming or joining processes could easily generate additional bifurcations this would also mean to sacrifice of one the main advantages of the process, which is the absence of laminations or joints.

1.2 Linear Bend Splitting (LBS)
The LBS process was developed to overcome the geometrical limitations of LFS and to facilitate linear stringer profiles for which the location of bifurcations is not restricted to the band edges but can be anywhere on the sheet plane [7]. In addition the process also allows the fabrication of sheet profiles with variable cross section [8] which opens up an enormous potential for structural light weight design.
The stage setup and process conduct for LBS is similar to LFS, with the main difference that the workpiece is not a plain sheet but an L- or U-section which is deformed at its bending radius as shown in Fig. 2 (left). With increasing splitting depth the processing zone, i.e. the volume between the radii of the supporting rolls and the splitting roll is filled, which is associated with a thickness reduction in the bending radius. In subsequent splitting steps a flange is formed and the thinned region of the former bending radius is elongated (see Fig. 2 (right)). At this stage LFS and LBS are identical with respect to the material flow in the processing zone or the strain distribution. [7]

Fig. 2. Process principle of LBS (left) [X] and cross-sectional view on profile evolution (right).

1.3 History and Future Trends for Flow Splitting and Bend Splitting

After the first presentation of the LFS process [16], nearly a decade of pre-commercial development has passed until LFS and LBS had their commercial launch. With regard to the state of commercialization of conventional SPD processes [4] it’s worthwhile to note that LFS and LBS are primarily applied for steel sections. This is a mass production market with much higher cost pressure than the markets in which ECAP has already entered or is likely to gain ground soon [4, 17]. Yet, considering the background of LFS and LBS, which were developed as modified roll forming processes, it’s no surprise that they are capable of high throughput continuous production using coil material. However, the fact that the processes are market ready doesn’t mean that there is little need for research left. Currently the processes are applied for their advantages over conventional roll forming in terms of integral design and geometric complexity. The increased strength that arises from the presence of local UFG gradient microstructures is a welcome feature but its potential is by far not exploited to the limits since it’s not sufficiently understood or quantified. Therefore, further investigations are required to probe the deformation mechanisms during the process to understand and facilitate modeling of the evolution of local properties. On the other hand, a generalized description of characteristic manufacturing induced properties which are more or less independent of the exact chemical composition or the processing parameters in detail would also be a great benefit [18]. Though certainly less precise than modeling approaches based on deformation mechanisms, such a description could help to exploit the lightweight potential in industrial product development processes where advanced material modeling such as VPSC or crystal plasticity approaches are usually not available or too expensive.

Furthermore, there is also progress to be expected in terms of breaking down the current limitations of LFS and LBS such as the linearity of the profiles. Flexible processes such as flexible flow splitting are currently developed [19] which are much more complicated in terms of tool geometry and process control and probably also in terms of property distributions.

3. Microstructures and Mechanical Properties

The microstructural evolution during LFS and LBS as well as the characteristic distribution of local mechanical properties in the resulting profiles are very similar [20]. Therefore, the
statements made in this section are valid for both processes even though only data from sheets deformed by LFS will be discussed.

Previous investigations have shown a characteristic hardness distribution in LFS profiles of High Strength Low Alloy (HSLA) steels [9, 13, 21, 22]. To evaluate in how far this distribution can be generalized, a comparison is drawn between a HSLA steel (H480LA) with 6 µm grain size, a ferritic stainless steel (1.4016) with 14 µm grain size and a mild steel (1.0332) with 16 µm grain size, that were processed with different LFS parameters (see Table 1).

Table 1. Processing parameters used for LFS of specimens from different ferritic steels.

|                | \(y_{\text{tot}}\) [mm] | \(y_{\text{inc}}\) [mm] | \(\alpha\) [°] | \(s_0\) [mm] | \(s_f\) [mm] |
|----------------|--------------------------|--------------------------|----------------|--------------|--------------|
| HSLA steel (H480LA) | 20                       | 1                        | 10             | 2            | 1            |
| Stainless steel (1.4016) | 18                      | 2                        | 10             | 2            | 1            |
| Mild steel (1.0332)    | 110                      | 0.5                      | 30             | 6            | 3            |

Parallel to the split surface all samples reveal a steep increase in hardness at the flange tips, which turns into a plateau of constant hardness over the largest part of the flange (see Fig. 3 (left)). There is only a slight deviation in terms of hardness level within the plateaus with respect to the different steels or processing parameters respectively. It's worthwhile to note that the variation in hardness between the plateau levels of the steels investigated is much lower than the variation between the as received hardness of the steels. Near the flange tips the hardness decreases significantly, approaching the values of the as received conditions. The hardness distribution perpendicular to the split surface is also similar for all of the profiles as shown in Fig. 3 (right), with error bars representing the standard deviation of 5 equivalent measurements. The depicted hardness gradients are representative for nearly the whole flanges, with the only exception of the regions near the flange tips where there are no plateaus of constant hardness parallel to the split surface. As a consequence, there is not just a plateau of constant hardness near the split surface as shown for a depth of 50 µm below the surface in Fig. 3 (left) but one for every given distance to the surface.

![Fig. 3. Hardness distribution in LFS profiles of different ferritic steels measured parallel to the split surface in a distance of 50 µm (left) and perpendicular to the split surface (right), legend applies for both diagrams. Dashed lines show the hardness levels of alloys in their as received condition. Error bars are similar for all hardness distributions (standard deviation 4 - 12 HV0.05) but only shown to the right for the sake of clarity.](image)

Regarding the slope of the hardness gradient in Fig. 3 (right) it shows that the gradient does obviously not scale with the flange thickness \(s_f\). There is a factor of three in between the mild steel and the HSLA steel in terms of flange thickness, yet both hardness gradients are nearly identical. Furthermore, there is also no observable effect from the different flange angles \(\alpha\) on the hardness distributions.
Fig. 4. Inverse pole figure maps from EBSD data of the microstructure in LFS profiles with different distances to the split surface. HAGBs (> 15 °) are marked black, LAGBs (2 ° till 15 °) are marked white.

The microstructure in the severely deformed regions of the LFS samples was analyzed in the cross section (y × z plane) of the profiles for two given distances to the split surface. The inverse pole figure maps with highlighted high angle and low angle grain boundaries shown in Fig. 4 are representative for the whole region of the flanges in which plateaus of constant hardness exist parallel to the split surface. Close to the split surface in a depth of 50 µm the microstructure of all three samples consists of ultrafine pancake grains with very high aspect ratios that are separated by mostly high angle grain boundaries (HAGBs) (see Table 2 for statistics). In a depth of 450 µm below the surface the microstructures are coarser than at 50 µm and exhibit significantly lower aspect ratios. Furthermore, the microstructures consist of a majority of low angle grain boundaries (LAGBs) so that they are rather heavily cold worked structures than UFG ones. The smaller (sub)grain size of the HSLA steel at 450 µm compared to the other two steels can be understood with respect to the decreasing strain with increasing distance to the surface [13]. Due to the smaller stain levels, the microstructural refinement is less distinctive and the grain size of the as received conditions have a stronger impact on the (sub)grain size.

Table 2. Microstructural characteristics of LFS profiles based on EBSD analysis.

| Distance to split surface | HSLA steel (H480LA) | Stainless steel (1.4016) | Mild steel (1.0332) |
|---------------------------|---------------------|--------------------------|---------------------|
|                           | Grain size          | HAGBs                    | Grain size          | HAGBs                    | Grain size          | HAGBs                    |
| 50 µm                     | 0.39 µm             | 71 %                     | 0.48 µm             | 62 %                     | 0.57 µm             | 60 %                     |
| 450 µm                    | 0.79 µm             | 43 %                     | 1.24 µm             | 41 %                     | 1.60 µm             | 35 %                     |

4. Discussion

Based on the results from previous investigations and those presented above, generalized findings concerning the characteristic properties of LFS and LBS profiles can be derived. Yet, there are also open questions with respect to evolution of these characteristic properties in terms of material flow and underlying deformation mechanisms.

4.1 Characteristic properties in LFS and LBS profiles

The comparison of local microstructures and hardness distributions in different LFS profiles shows that there is a characteristic gradient perpendicular to the split surface and constant properties parallel to the split surface for each given distance to the surface. Thus, the local hardness and also local microstructural parameters such as grain size, aspect ratio or HAGB fraction can be described in good approximation just by one geometric parameter which is
the distance to the split surface. The only exceptions to this rule are the flange tips, which are formed in the first stages of the process, that exhibit not just a gradient perpendicular but also parallel to the split surface. The characteristic gradient that defines the properties over the largest part of the deformed flanges, appears to be relatively insensitive to the processing parameters or the alloy used, at least as far as steels with a mostly ferritic microstructure are concerned (see also [22, 23]). Neither the flange angle $\alpha$ nor the flange thickness $s_f$ or the sheet thickness $s_0$ seem to have a strong effect on the resulting distribution of mechanical properties. For all LFS parameters and materials investigated in this work or previously [13, 20-23], the gradients are very similar exhibiting a steep decrease in hardness with increasing distance to the split surface to a depth of 300 to 500 $\mu$m and a flatter decrease or even constant hardness down to the lower side of the flange. This gradient correlates with a decrease in HAGB fraction and aspect ratio as well as an increase in grain size.

Based on the similarity of the results obtained from different geometries and materials it seems to be a reasonable approach to run an empirical analysis on the relation between the mechanical properties in the as received condition and the hardness distribution after LFS or LBS. A lower bound approximation for the expected increase in strength would be an easy but efficient tool for the product development that could help to take more advantage of the lightweight potential of the processes without going through the effort of producing and characterizing prototypes [18].

4.2 Material flow and deformation mechanisms in LFS

The fact that there is no continuous gradient in microstructure and mechanical properties parallel to the flange surface is quite surprising, taking into account that a steady increase in strain from the flange tips towards the splitting center was shown by FE simulation [13]. The expected correlation of increasing strength with increasing strain can only be observed near the flange tips which are formed in the first few passes. Thus it seems that classic work hardening behavior ceases to be valid after a certain flange length or in other words a certain level of plastic strain is reached.

So far the constant properties parallel to the flange surface and the absence of cracking were attributed to the UFG microstructures that evolve during the LFS process. It is known from the literature on SPD that properties and microstructures of UFG metals become nearly independent of further deformation after a certain level of strain is exceeded, which corresponds to strain hardening stage IV and V [24-26]. It can’t be ruled out that stage 4 strain hardening is the reason for a very small increase in the local strength from the flange tips towards the splitting center, which could be less than the typical scatter of hardness measurements. However, this assumption would imply that the strain does not increase by several orders of magnitude from the onset of the (apparent) hardness plateau towards the splitting center.

To estimate the maximum strain at the splitting center, the LFS process will be regarded as an enlargement of the surface area at the band edge. Consequently, the strain at the surface can be calculated from the increase in surface area during the individual splitting stages. However, the strain is not distributed homogeneously across the flange surface due to the fact that the deformation is confined to a relatively small processing zone, which results in the aforementioned strain gradient. The profile geometry and increase in surface area were measured for a mild steel profile similar to the one shown in this work [7]. The analysis of the surface area shows that the increase in length of the band edge $\Delta L$ is approx. 0.95 mm for each splitting step having an incremental splitting depth of 0.5 mm. Based on these data the total strain at the splitting center can be estimated based on the following assumptions. First, it is assumed that the size of the processing zone in the cross-section is similar to the sheet thickness. The second assumption is that the strain distribution is homogeneous within the
surface area of the processing zone. From this it follows that the total strain at the splitting center $\varepsilon_{\text{tot}}$ can be expressed by a simple power law function:

$$\varepsilon_{\text{tot}} = \left(1 + \frac{\Delta L}{s_0}\right)^n - 1 \quad \text{[Eq. 1]}$$

with $n$ being the number of splitting steps. For the above example ($\Delta L \approx 0.95 \text{ mm}$, $s_0 = 6 \text{ mm}$) it follows that the total strain at the splitting center after 110 splitting steps ($y_{\text{tot}} = 55 \text{ mm}$) is around $10^7$ which corresponds to a true strain of 16 (see Fig. 5 (right)). Though this is just a very rough estimate of the strain, it demonstrates the severity of plastic deformation that occurs during LSF to very high splitting depths.

![Fig. 5. Schematic representation of the profile cross section during LFS for a 6 mm sheet (left) with corresponding increase in surface area at the band edge and engineering strain at the splitting center (right).](image)

The enormous strain values in this example show that the assumption of an enlargement of the surface area is implausible with respect to the current understanding of strain hardening in metals. Another strong argument is that there is not just one plateau of constant hardness, which one could interpret as strain hardening stage V, but different ones for every distance to the split surface. Consequently a new model for the material flow in LFS and LBS is required to overcome the apparent contradiction between the simple surface enlargement theory and the characteristic distribution of local microstructures and mechanical properties.

![Fig. 6. Schematic material flow through the processing zone (marked red) in LFS / LBS.](image)

Since there is a characteristic gradient in microstructure and mechanical properties that evolves after a certain splitting depth, it is reasonable to assume that the processing zone in LFS and LBS reaches a steady state in terms of size and strain distribution. From this assumption it follows that the mechanical properties of the material that has passed through this zone only depend on the route it took which leads to the schematic material flow model shown in Fig. 6. The only problem with this model is that it requires new material to enter the
split surface based on the fact that by solely enlarging the surface area a constant strain distribution can never be reached. Since for both processes neither cracks nor localized deformation such as shear bands are observable, the missing link to completely understand the material flow is related to the question how new material can enter the surface without cracks.

There is an ongoing discussion concerning the deformation mechanisms during SPD processing especially when reaching the steady state where microstructural refinement and strain hardening saturate. Numerical calculations typically show that dislocation based plasticity is the dominant deformation mechanism at grain sizes above 20nm [27, 28] though the actual transition size may be higher considering the limitations of MD simulation [29]. Yet, experiments reveal that the transition grain size from grain boundary mediated processes to dislocation plasticity is not far from what is predicted by MD [30, 31]. Still, there is also experimental evidence for localized deformation along grain boundaries in the UFG regime [32], often referred to as grain boundary sliding. Yet, this term is somewhat misleading since it is usually refers to plasticity carried by grain boundary diffusion as in superplasticity or Coble creep.

In the present case of ferrite steels with minimum grain dimensions (pancake thickness) of around 80 – 100 nm [9] being deformed at room temperature and at strain rates which are typically in the order of $1 - 10 \text{s}^{-1}$ [13], it is relatively save to rule out significant contributions from diffusional processes. The extreme texture intensities of bcc rolling components that have been observed near the split surface [14] are also a strong indicator in this respect, though shear components may also occur under certain feed rates and lubrication conditions [23]. Nevertheless, the question how dislocation based plasticity, which is most likely the dominant carrier of plasticity during LFS and LBS, can generate an increase in surface area without strain hardening still remains unsolved. This is the biggest challenge for both the experimental and numerical characterization of LFS and LBS, as mapping the local material flow during the process is very difficult from an experimental point of view and validating new material models that predict the local hardening behavior without knowing the material flow is hardly possible either.

5. Summary

Integral sheet metal design by LFS and LBS is a promising approach for the production of complex profile geometries which combines the advantages of continuous processing with the superior strength of local UFG microstructures as a consequence of the severe strains induced. The severely deformed regions of the profiles exhibit a characteristic gradient in microstructure and mechanical properties. This gradient is relatively insensitive towards the specific processing parameter and the alloy composition, at least as far as ferritic steels are concerned. The presence of a characteristic gradient perpendicular to the split surface is attributed to the formation of a steady state of deformation in the processing zone, with the resulting material properties being a function of the path through this zone. Still, further research is needed to clarify the deformation mechanisms that lead to a steady state of deformation in the processing zone in spite of the nominal increase in strain in every splitting step.

Acknowledgments

The authors thank the German Research Foundation (DFG) for founding the present work, which has been carried out within the Collaborative Research Centre 666 “Integral sheet metal design with higher order bifurcations — Development, Production, Evaluation”.

References

[1] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 Prog. Mater. Sci. 45 103–189
[2] Valiev R Z et al 2006 JOM 58 33–36
[3] Azushima A et al 2008 CIRP Ann. Manuf. Technol. 57 pp 716–735
[4] Lowe T C 2010 Mater. Sci. Forum 667-669 pp 1145–1151
[5] Raabe D, Ponge D, Dmitrieva O and Sander B 2009 Adv. Eng. Mater. 11 pp 547–555
[6] Groche P, Vucic D and Jöckel M 2007 J. Mater. Process. Technol. 183 pp. 249–255
[7] Groche P, Ringler J and Vucic D 2007 Key Eng. Mater. 344 pp 251–258
[8] Groche P, Ringler J and Abu Shreehah T 2009 CIRP Ann. Manuf. Technol. 58 pp 263–266
[9] Bohn T, Bruder E and Müller C 2008 J. Mater. Sci. 43 pp 7307–7312
[10] Li W L, Tao N R and Lu K 2008 Scripta Mater. 59 pp 546–549
[11] Neugebauer R, Sterzing A and Bergmann M 2011 Mat.-wiss. u. Werkstofftech. 42 pp 593-598
[12] Segal V M 1995 Mater. Sci. Eng. A 197 pp 157–164
[13] Müller C et al 2007 Mat.-wiss. u. Werkstofftech. 38 pp 842–854
[14] Bruder E 2012 J. Mater. Sci. 47 pp 7751–7758
[15] Lee J C, Seok H K, Han J H and Chung Y H 2001 Mater. Res. Bull. 36 pp 997–1004
[16] Groche P et al 2003 New tooling concepts for future roll forming applications Proc. 4th International Conference on Industrial Tools ed K Kuzman (Celje: Slovenia) pp 121–126
[17] Valiev R Z, Sabirov I, Zhilyaev A P and Langdon T G 2012 JOM 64 1134–1142
[18] Groche P et al 2012 CIRP Ann. Manuf. Technol. 61 pp 163–166
[19] Storbeck M et al 2013 Future Trends in Production Engineering ed G Schuh, R Neugebauer and E Uhlmann (Berlin-Heidelberg: Springer) chapter 17 pp 161-179
[20] Kaune V and Müller C 2012 Mater. Sci. Eng. A 535 pp 1–5
[21] Bruder E, Bohn T and Müller C 2008 Mater. Sci. Forum 584-586 pp 661–666
[22] Schuster J, Bruder E and Müller C 2012 J. Mater. Sci. 47 pp 7908–7913
[23] Ludwig C et al 2013 Mat.-wiss. u. Werkstofftech. 44 pp 601–611
[24] Zehetbauer M and Seumer V 1993 Acta Metall. 41 577–588
[25] Estrin Y et al 1998 Acta Mater. 46 5509–5522
[26] Pantleon W 2010 Mater. Sci. Forum 667-669 pp 205–210
[27] Schiotz J 2004 Scripta Mater. 51 837–841
[28] Vo N Q et al 2008 Phys. Rev. B 77 134108
[29] Schäfer J, Stukowski A and Albe K 2013 J. Appl. Phys. 114 143501
[30] Skrotzki W et al Acta Mater. 61 7271–7284
[31] Ivanisenko Y et al 2009 Acta Mater. 57 3391–3401
[32] Yang K et al 2010 Acta Mater. 58 967–978