University of Pardubice
Faculty of Transport Engineering

DETERMINATION OF THE LIMIT DEFORMATION STATE OF IF STEEL UNDER INCREASED STRAIN RATES CAUSED BY LOCALIZED DEFORMATION IN AUTOMOTIVE STAMPED PARTS

A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (ANNOTATION)

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Abstract

The presented dissertation thesis deals with the deformation behavior of the investigated type of anisotropic interstitial-free (IF) steel under various deformation conditions. This type of steel is being used for stamping of complex-shaped automotive body parts (e.g., doors, hood, inner tunnel) and thus represents a deep-drawing material used in the automotive industry.

The presented analyses focus on the material response under various stress/strain conditions and different strain rates, as well as on the microstructural evolution of deformation using crystallographic analyses (EBSD). The motivation for the presented study is the real production state, where the complexity of parts and the localization of the deformations place extreme demands on the technological processes and the formability of the materials. The resulting effects are analyzed in this thesis using actual stamped parts with graded levels of deformation. The occurrence of localized deformation in critical positions of the stamped parts is influenced by several factors affecting the response of the plastically deformed material. Therefore, material tests under various loading conditions were incorporated to describe the individual possible influences. Part of the dissertation also focused on exploring the potential for non-destructive measurement of the state of plastic deformation using the Barkhausen noise measurement method.

The obtained results revealed a significant influence of different loading conditions on the mechanical response of the investigated material type and a varying tendency towards localization of deformation. The results are presented within the respective chapters and may significantly impact the occurrence of localized deformation in critical positions of real stamped parts. The typical example of deformation state in these critical positions is presented in the work. The suitability of the chosen non-destructive method (MBN) for capturing the level of plastic deformation in the investigated material was confirmed.

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1 Introduction

The main trends in automotive research and development in recent years have been to reduce vehicle weight, improve safety, and focus on electromobility. In addition to the introduction of new materials for weight reduction and safety, there are increasing demands on the production of individual components. In stamping, for example, production speeds are increasing, and efforts are being made to maximize material utilization. Forming speeds, tool speeds, and therefore local strain rates are increasing. We are also seeing greater localization of deformation during forming. Design trends are leading to an increase in the number of geometrically complex parts. That places extreme demands on the technological processes and the formability of the materials. Significant thinning of the stamped sheets at critical positions, can lead to crack propagation during stamping or in subsequent manufacturing processes. This problem requires both investigation and adjustment of the stamping process and conditions, as well as a thorough inspection of the material condition before and after stamping, including from a microstructural perspective. The requirements for inspecting the material condition after the stamping process are generally aimed at non-destructive measurement of the material response in identified critical positions so that the stamping process can be adjusted based on the obtained results.

Current research and development is therefore focused on these requirements, which arise from real production needs. Specifically, the aim is to use appropriate non-destructive methods to determine the actual state of materials both at the start of the production process and after stamping, ensuring that the chosen method accurately reflects the state of the material in relation to its current microstructural deformation state. However, in order to make such an assessment of the material after stamping, it is first necessary to identify the deformation limit state of the material and the effects that lead to a reduction in plasticity at these critical positions.

This also outlines the motivation behind the presented dissertation. The present study focuses on determining the critical state of anisotropic interstitial-free (IF) steel including electrolytic zinc coating by monitoring the deformation behavior of the material also from a microstructural point of view. The research examines the evolution of the deformation mechanism under different stress-strain states and strain rates and compares it with the actual state of stamped parts. In addition, a non-destructive method of measuring Barkhausen noise is validated to capture the evolution of plastic deformation in the examined IF steel. This type of steel is commonly used for stamping complex-shaped car body parts (e.g., doors, hood, inner tunnel) and thus represents a deep-drawing material used in the automotive industry.

The effect of localized deformation on stamped parts has several impacts, both on the local material state in terms of macro/microscopic deformation, and on the deformation process itself due to material flow at critical positions with increased strain rates. The issue of stamping is mainly addressed in terms of technological parameters of stamping [1-4], material formability [5-7], and forming simulations [2, 8, 9], but not the actual state of the stamped material after stamping. Data on the actual state and evolution of material deformation at critical positions of stamped parts and the limit state of plasticity, are not available and efforts are being made to solve this problem.

Part of the presented thesis also focuses on the behavior of the tested anisotropic material (IF steel) under investigation at high strain rates, which can occur in areas of significant deformation localization even in this type of production and application. These are studied under various stress/strain conditions that can generally occur in stamped parts. Relatively little information is available even on this subject and for the specific type of material being investigated, which by its nature is not designed for high strain rate use. This information tends to focus on material response at higher strain rates [10, 11], or its determination for simulations using material models [12-14], but not on the effect of speed on deformation evolution from a microstructural perspective or on failure initiation.

In addition to the strain rate mentioned above, other parameters influence the resulting deformation flow and its localization leading to failure (the limit state). Determining the limit state of a material for a given purpose can be done in many ways, such as the forming limit curve from forming limit diagrams or the tensile strength limit from standard tensile tests. From a material point of view, it is desirable to investigate and define its limit state from a microstructural point of view, based on reaching the limit of plastic capacity. Many parameters influence the plastic capacity of the material and the deformation state itself. These parameters are also often included in analytical material models used to describe and predict material behavior. They are also used in numerical simulations, for example, to evaluate formability.

2 Objectives of the Research Work

As discussed in the introduction, the current challenges in automotive sheet metal forming require the quantification of the limit state of the material and its plastic deformation. This assessment should take into account not only the local thickness reduction of the sheets, but also the internal structure of the material and any other defects resulting from plastic deformation. This involves describing and quantifying the microstructural deformation mechanisms, including changes in grain shape and orientation, and the role of impurities and precipitates on microcrack initiation under specific stress-strain conditions and strain rates. By determining the limit state of the material, this knowledge can then be integrated with an appropriate non-destructive method to monitor the condition of identified critical positions.

The main objective of the dissertation thesis is to determine the limit state of the plastic capacity of a material with inherent anisotropy under the influence of deformation localisation and the resulting increased strain rate. This includes the following specific objectives using a presented type of analysed Interstitial-Free (IF) steel:

- Analysis of the microstructural state of deformation at defined stages of plastic deformation in the studied anisotropic steel.
- Description of structural changes, including the evolution of anisotropy in the steel, leading to the limit of plastic deformation.
- Determination of a suitable parameters to quantify plasticity depletion in steel.
- DIC mapping of material deformation in uniaxial static tensile tests using the ARAMIS system.
- Evaluation of the strain rate influence on deformation localization using uniaxial dynamic tensile tests.
- Mapping of differences in the effect of strain rate increase relative to the initial crystallographic orientation of the steel.
- Defining the actual influence of the metallurgical quality of the analysed steel on the limit of plastic deformation; assessment of the possibility of quantifying the impact of impurities on microcrack initiation.
- Analysis of the intensity of strain hardening as a function of strain localisation/strain rate using local yield strength indentation measurements.

- Verification of the suitability of the chosen non-destructive method (Barkhausen noise measurement) for monitoring the limit state and plastic deformation evolution of the tested material.
- Integration of the above-mentioned experimental analysis with the monitoring of the corresponding parameters in real stamped parts.

3 Used Methods for Limit State Analyses

In order to fulfil the defined objectives and requirements of the dissertation thesis, the available equipment/technologies of the Educational and Research Centre in Transport of the Faculty of Transport Engineering were mainly used. However, part of the tests was carried out in DYMA Lab at Ghent University, and for the Barkhausen noise measurement was done at UNIZA. The methods used for limit state analysis can be divided into mechanical testing and material analysis. The main methods are briefly described below.

For mechanical testing of both standardized and non-standardized tensile samples, two devices were used.

For **static tensile tests**, a ZwickRoell Z030/TH2A tensile machine with a load capacity of 30 kN was used. The strain rate for the static tensile tests was set at 0.002 s^{-1}. GOM's Aramis 4M optical measurement system was also used in the static tensile test setup. This system allowed the Digital Image Correlation for deformation monitoring during the tests. A similar system from Match ID was used for the dynamic bulging tests.

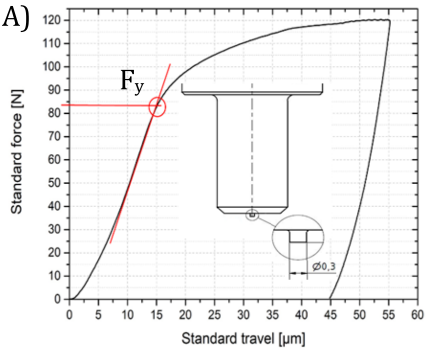
Dynamic tensile tests at increased strain rates were carried out using the INOVA electro-hydraulic system with Inova TestControl software. This system allows tensile tests to be performed at impact velocities of 5, 10 or 15 m/s. The set-up was used to determine the effect of high strain rates on the deformation behaviour, plastic capacity and dynamic hardening of the tested material under uniaxial tensile conditions.

For the material test under biaxial tension with no influence of friction, **quasi-static bulge tests** were used. These tests were performed at the Dynamic Material Testing Laboratory (DYMA Lab) of Ghent University. The tests were run/stopped at incremental bulge deformations to capture different stages of material deformation.

The **dynamic bulge tests** were carried out in the same laboratory using a uniquely modified test set-up based on the Split Hopkinson Pressure Bar (SHPB) test principle. As with the quasi-static variant, incremental bulge deformations were obtained. Surface deformation measurements were also obtained using Digital Image Correlation (DIC).

Indentation tests were used to quantitatively evaluate material hardening under different loading conditions and strains. Both Vickers hardness measurements and unconventional cylindrical indenters were used. A ZWICK ZHU 2.5/Z2.5 universal hardness testing machine with continuous force and deformation record was used for the measurements. Depth Sensing Indentation tests using unconventional cylindrical indenters allow the local state of the material after deformation to be recorded. By applying Hencky's hypotheses of material response based on slip lines [15], the local yield strength of the material can be obtained, corresponding to the conventional yield strength from tensile tests. This approach can be advantageously used to quantitatively evaluate the local state of the material after deformation, such as the deformation state of critical position in a stamped part or a deformed specimen after a mechanical test. An example of this application is shown in Figure 4.1.

A)



B)

$$\frac{\boldsymbol{F_y}}{\boldsymbol{A}} = \mathbf{2,57}\boldsymbol{Ri}$$

F_y: *Force at the yield point*

A: *Base area of cylinder*

Ri: *Indentation yield strength*

Figure 4.1 Indentation test record A); Conversion formula for indentation yield strength B)

Scanning Electron Microscopy (SEM) was the main tool used for material analyses, using a TESCAN VEGA 5130SB, Tescan MIRA S6123 and a QUANTA FEG 450. The TESCAN VEGA and MIRA were equipped with a Bruker Quantax 200 EDX microanalyser for chemical analyses and a Bruker e-Flash EBSD analyser for crystallographic analyses. The QUANTA FEG was equipped with an EDAX EBSD analyser. In addition to specific analyses, Scanning Electron Microscopes were used primarily to examine the presence of microcracks, inclusions and impurities, as well as to accurately measure sample dimensions (thickness).

EBSD analyses were carried out for crystallographic analyses of the evolution of microstructural deformation in the tested material. These analyses were carried out on both planar and cross-sectional samples. The evolution of misorientation was monitored using grain boundaries and Kernel Average Misorientation (KAM), as well as the orientation of microstructural textures as a function of the type and intensity of deformation. For this purpose, a method to evaluate the proportion of each major texture orientation was developed (referred to as the RGB method). This method works on the principle of determining the primary proportion of RGB colours represented within individual pixels of inverse pole figures, as shown in Figure 4.2. This is similar to the Orientation Distribution Function (ODF) and allows the quantification of the tendency to rotation of textures in certain planes.

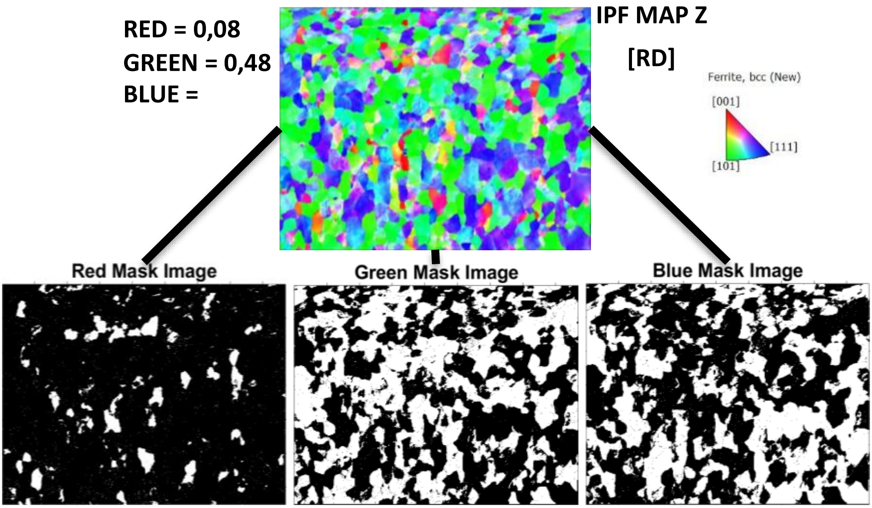


Figure 4.2 Example of evaluating the proportion of predominant RGB

4 Investigated Material – IF Steel (DC06)

The investigated material is a type of conventional IF steel (grade DC06), which is an anisotropic steel with a purely ferritic microstructure (Figure 5.1 A)), featuring an intragranular distribution of fine carbides and an electrolytically zinc-coated surface layer of approx. 10 μm thickness. The studied material represents a type of steel commonly used for deep drawing of stamped parts, which offers very high formability. This formability is achieved by an inherent plastic anisotropy which develops during the manufacturing process of the steel and results in a preferentially oriented gamma fibre structure in the thickness direction of the sheet - γ (<111>||ND) – Figure 5.1 B).

The chemical composition is given in Table 5.1. Mechanical parameters were obtained using standard tensile tests (strain rate 0.002 s^{-1}) in three directions relative to the rolling direction (0°, 45°, 90°) and the results are summarised in Table 5.2. Small differences were observed between directions. The differences are discussed further in relation to the biaxial tension response, see Section 6.3. The most significant differences were found in the coefficient of plastic anisotropy, with the lowest value measured for the 45° orientation and the highest for the 90° orientation.

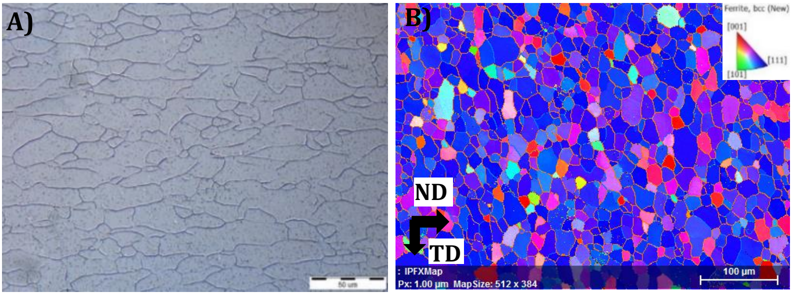


Figure 5.1 A) Microstructure of IF steel, magnification 500x; B) predominant texture γ fibre (<111>||ND)), magnification 250x

Table 5.1 Chemical composition of the analysed IF steel [wt. %]

Elements	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Ti
[wt.%]	0.0028	0.099	0.011	0.0084	0.002	0.032	0.019	0.014	0.048	0.051

Table 5.2 Mechanical properties of the investigated IF steel from standard tensile tests

Direction to RD	$Rp_{0,2}$ [MPa]	R_m [MPa]	A_g [%]	A_{80} [%]	n [-]	r [-]	$\bar{r}$ [-]	Δr [-]
90°	151	288	26,6	45,7	0,26	2,56		
	159	287	24,7	42,9	0,25	2,19		
	157	286	25,3	43,3	0,25	2,29		
	160	288	24,7	44,4	0,25	2,26		
Average	**156,8**	**287,3**	**25,3**	**44,1**	**0,25**	**2,33**		
St. Dev.	**4,03**	**0,96**	**0,90**	**1,26**	**0,01**	**0,16**		
0°	158	298	26,1	45,7	0,25	1,92		
	153	288	26,1	46,1	0,25	2,02		
	153	289	27,0	45,9	0,25	1,86	**1,835**	**0,61**
	157	287	25,8	42,7	0,25	1,99		
Average	**155,3**	**290,5**	**26,3**	**45,1**	**0,25**	**1,95**		
St. Dev.	**2,63**	**5,07**	**0,52**	**1,61**	**0,00**	**0,07**		
45°	175	295	24,3	42,3	0,23	1,62		
	163	293	24,5	42,5	0,24	1,51		
	162	293	24,6	44,7	0,24	1,48		
	165	298	25,1	44,2	0,24	1,52		
Average	**166,3**	**294,8**	**24,6**	**43,4**	**0,24**	**1,53**		
St. Dev.	**5,97**	**2,36**	**0,34**	**1,20**	**0,00**	**0,06**		

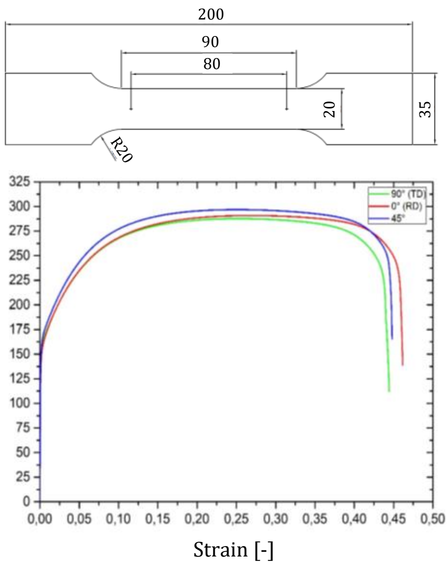


Figure 5.2 Tensile curves in 3 directions relative to the rolling direction and samples geometry

5 Obtained Results

Selected results are presented below, highlighting the key findings from the different chapters of the dissertation thesis.

5.1 Deformation Development under Uniaxial Loading

Uniaxial tensile tests were carried out on different types of specimen's geometries and at different strain rates, both at quasi-static strain rates (0.002 s^{-1}) with DIC measurements and in high-speed impact tests at strain rates of 60, 110, 135, 275, 340 s^{-1}.

Quasi-static tensile testing was also used to measure the magnetic response of the material using Barkhausen noise. Samples were incrementally deformed (Figure 6.1 A)) to near failure and their deformation state was analysed using MBN measurements (Figure 6.1 B), crystallographic analyses (EBSD) and also indentation measurements.

Strains	Homogenous strains							Non homogenous strains			
%	1.9	3.8	7.4	9.3	16.6	24.0	27.5	31.3	35.0	38.8	42.5

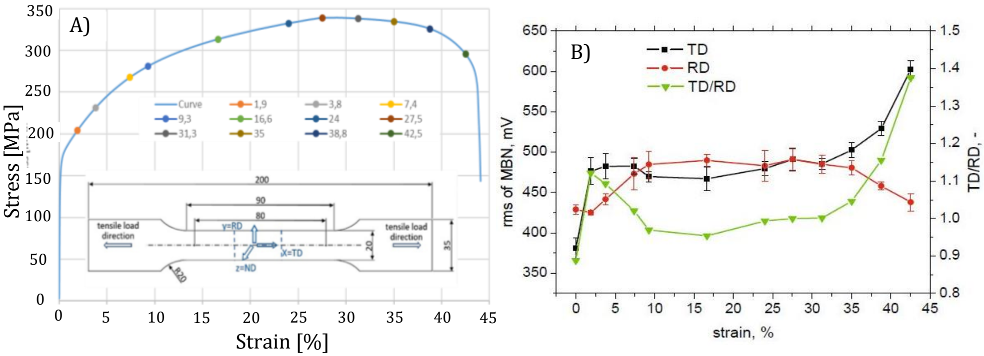


Figure 6.1 A) Quasi – static tensile curve with strain increments of tested samples; B) Results of non-destructive MBN measurement in TD and RD

The results of the MBN measurements are shown in Figure 6.1 B). The effective values of the measured signal (rms) are very similar in both directions for lower and medium levels of deformation. At higher levels of deformation, starting from 35%, there is a significant increase in the effective signal value in the TD direction and a decrease in the RD direction (the response of the method to the development of plastic deformation was confirmed). This is influenced by the increased level of minor strains that really affect the mechanical parameters obtained in uniaxial tensile tests as well as micro cracks initiation on present impurities. Minor strain also affects the tendency of crystallographic textures to rotate, as shown in Figure 6.2. During the inhomogeneous deformation were induced rotations towards [111] in RD together with [101] in TD. In addition to the tendency to rotate, the minor strain has a positive effect on material localisation, leading to a gradual thinning towards failure.

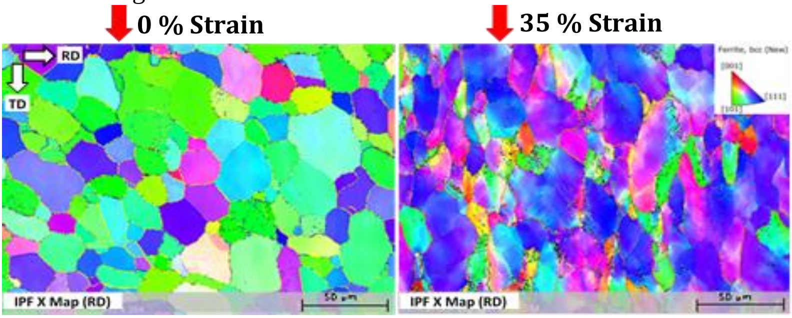


Figure 6.2 Tendency of crystallographic textures rotation in RD

High speed tensile tests were carried out to record the effect of increased strain rates on the mechanical response of the tested steel. The resulting tensile curves at various strain rates are shown in Figure 6.3. An important finding is the significant increase in dynamic yield strength at the studied strain rates. This range of strain rates may be also achieved in the context of localised deformation in critical positions of stamped parts. Therefore, this range of strain rates may result in local hardening of the material, leading to a reduction in plasticity. The plastic straining shows a gradual increase in strain hardening, which is significantly lower compared to static loading and can be considered a natural response due to the significant hardening at the yield point and the limitation of the hardening mechanism by the high-speed loading.

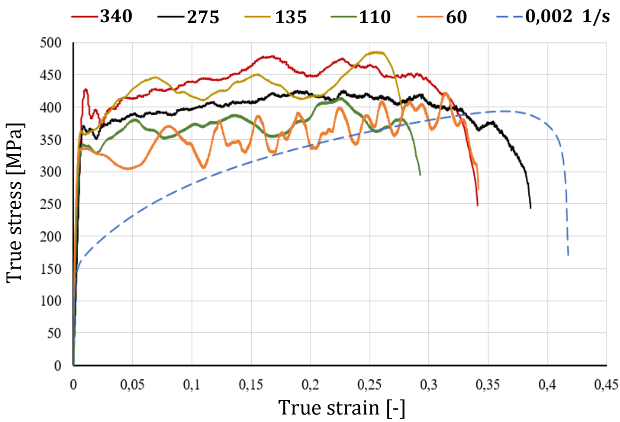


Figure 6.3 Results of impact tests in comparison with quasi-static response

5.2 Development of Plasticity under Plane Strain Conditions

The evaluation of plane strain conditions was carried out to allow comparison of the measured samples with real stamped parts. In these parts, plane strain is typically a critical condition, which is also reflected in the standard Forming Limit Diagram (FLD). In order to evaluate the achieved state of plane strain, a tensile specimen with a special geometry was designed and produced by laser cutting as shown in Figure 6.4 A). Again, the **quasi-static** and **dynamic/impact** conditions were investigated.

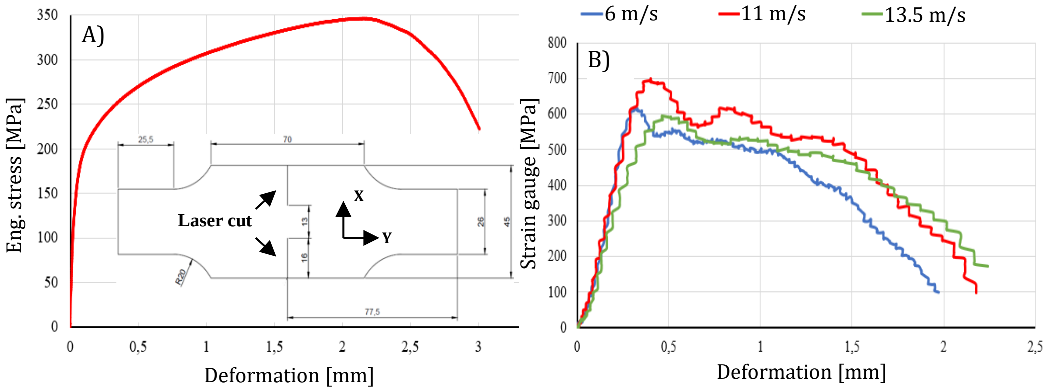


Figure 6.4 Mechanical response under A) quasi-static loading; B) impact loading

The initial tests involved uniaxial loading of specimens at a quasi-static rate of 1 mm/min with continuous optical measurement for Digital Image Correlation (DIC). The local strain rate in the localisation region and its evolution were monitored. A significant increase in strain rate due to localisation was observed, with an increase of up to approximately 2 orders of magnitude (Figure 6.5). This finding is crucial for accurately estimating the effect of deformation localisation on strain rate increase, even in critical positions of stamped parts. The mechanical response of the material under plane-strain conditions showed higher values for the mechanical parameters obtained compared to conventional tensile testing, as detailed in Section 6.1. The effect of minor strains was eliminated. The sample was then subjected to EBSD analysis and indentation testing in the sections (S and 2mm). The evolution of the preferential γ-fibre texture with respect to plastic deformation and sheet thickness is shown in Figure 6.6.

Impact tests were performed to investigate the effect of increased strain rates. Based on the assumption of identical deformation behaviour up to localisation at the yield point, the strain rates were recalculated using the deformation rates obtained from 'quasi-static'

DIC measurements. This resulted in deformation rates of approximately 180, 330 and 405 s-¹. The effect of different impact velocities within the tested range on the plane strain conditions was not significant (Figure 6.4 B)). However, there was a significant increase in dynamic yield strength of approximately 200% compared to static loading.

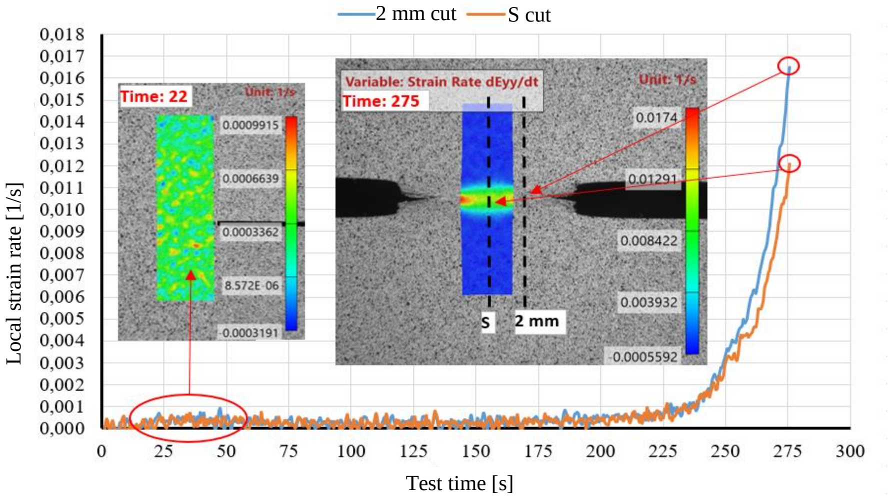


Figure 6.5 DIC measurement – the increase of local strain rate

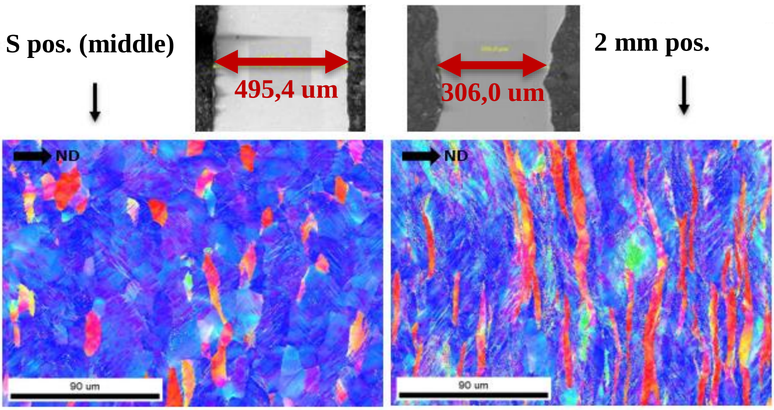


Figure 6.6 EBSD IPF maps in ND – the evolution of γ-fibre texture

From the obtained results and its comparison with tensile tests, it is evident that the type of deformation has a significant effect on the mechanical response of the material. Under plane strain conditions there is a significant increase in strengthening, which can be further enhanced by deformation localisation leading to a significant increase in strain rate. This effect probably occurs in critical areas of stamped parts where plane strain conditions are localised.

5.3 Evolution of the Deformation under Biaxial Load

Biaxial tension tests, one of the most used technological methods for assessing the formability of materials, were included to fully capture the main deformation states. The bulge testing was used for this, with minimizing the effect of friction at the media-sample surface contact. The tests were carried out during a research internship at Ghent University in the Dynamic Material Testing Laboratory (DYMA Lab). Unique equipment was used for both **quasi-static bulging** and **impact dynamic bulging** tests. As shown in the figure 6.7, these tests were also carried out with incremental levels of bulging.

This approach was used to capture the effect of biaxial loading on the development of deformation localisation and strain hardening, even at high strain rates. Bulging values were obtained from subsequent measurements. The effect of strain rate on localisation and plastic capacity is evident from these measurements, with higher maximum bulging values observed under static loading conditions.

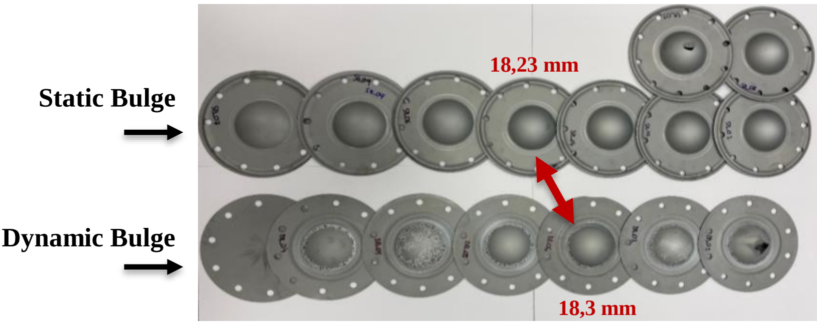


Figure 6.7 Static and dynamic bulge samples

The dynamic tests were monitored using DIC, which showed a relatively small effect of material anisotropy in the RD/TD directions, Figure 6.8. However, the measurements showed a tendency for a slightly higher deformation in the TD, leading to the final necking in the RD direction and consequent failure initiation. This effect corresponds to measured mechanical parameters from the tensile tests, which indicated a slightly higher ductility in the RD direction.

The initial material analyses compared two samples with identical levels of bulging (18,23 and 18,3 mm) tested at different loading rates (quasi-static vs. dynamic – of speed impact 16 m/s). The analyses confirmed the effect of loading speed on the deformation localisation around the sample apex under the given loading conditions. In polished sections taken along the TD direction, measurements were taken over a 35 mm length in the bulging apex. Thickness measurements (using SEM) and indentation tests were carried out to compare the loading speed effects. The gradients are shown in Figure 6.9. The influence of loading speed on its localization and strengthening under biaxial loading conditions is evident from the gradients. The results obtained will be supplemented by subsequent analysis of further selected samples from both sets presented, including microstructural EBSD analysis around the bulge apex.

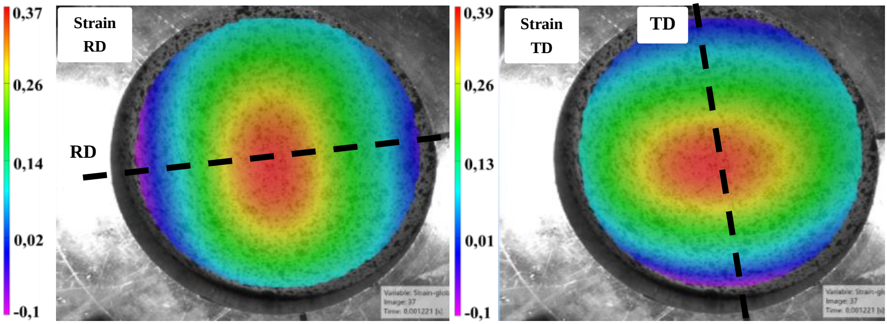


Figure 6.8 DIC strains in TD/RD directions

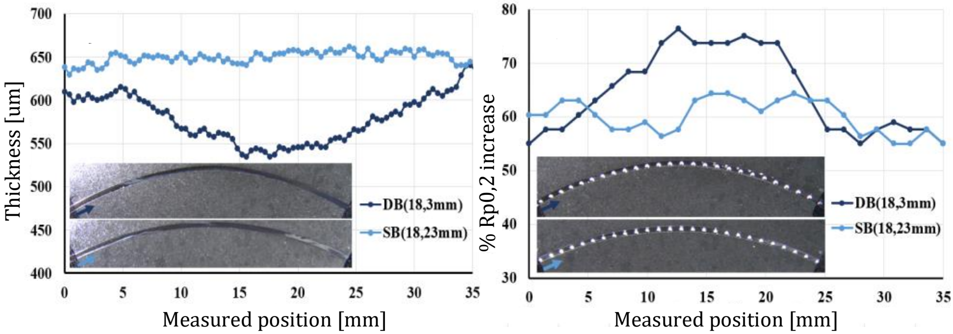


Figure 6.9 Thickness and indentation measurement results

5.4 Analyses of Critical Positions of the Real Stamped Parts

The next stage of the tests was carried out on real stamped parts produced from the same batch of the investigated material. Stamping with incremental levels of deformation (variation of stroke level) was also carried out on a try out press. The analyses focused on the study of the limit deformation state in critical positions of the obtained real stamped parts.

The occurrence of localised thinning is influenced by several factors, primarily related to the local geometry of the part and the level of friction at the tool/material interface. This results in the typical appearance of asymmetric localised thinning with predominant uneven tensile loading and limited plastic flow from the thinned region, leading to typical type of fracture, as shown in Figures 6.10 and 6.11.

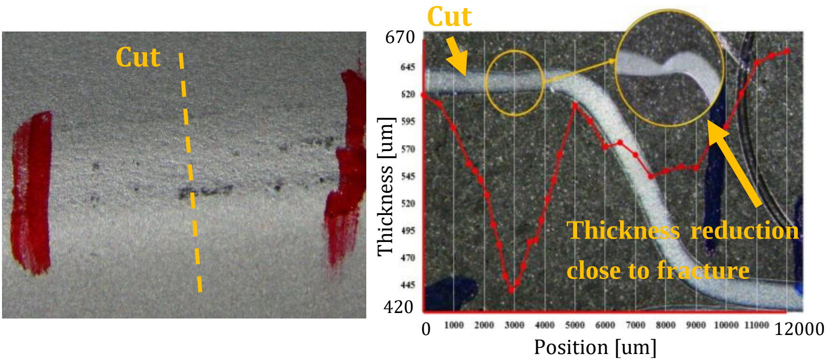


Figure 6.10 Thickness localization in the critical position

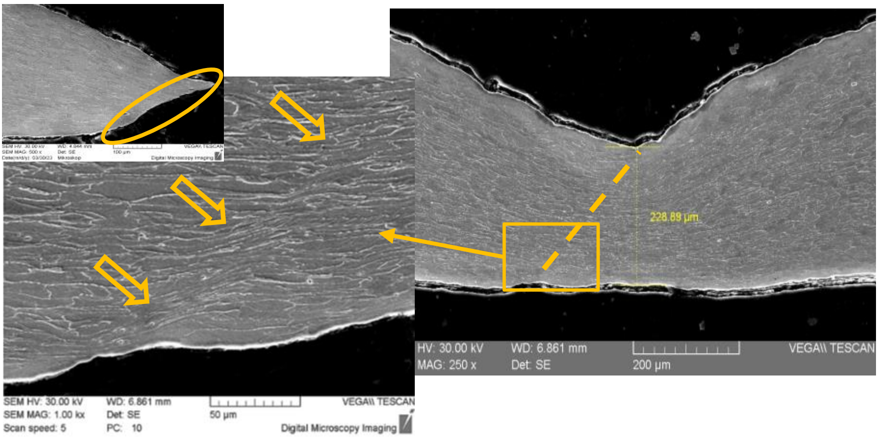


Figure 6.11 Typical fracture in the critical position

Attention was focused on monitoring the evolution of microstructural deformation as it relates to the strain state, in particular thinning. Crystallographic analyses were carried out on various thicknesses of the thinned areas to monitor the evolution of microstructural deformation, an example of EBSD IPF maps is shown in the figure 6.12. This was supported by indentation measurements. Selected crystallographic parameters were used to capture the state of deformation, including observation of crystallographic texture rotation, KAM maps/distribution and monitoring of the evolution of the LAGB fraction in the measured positions. **These approaches and measurements were carried out for all types of analyses presented, even if not detailed in this summary.**

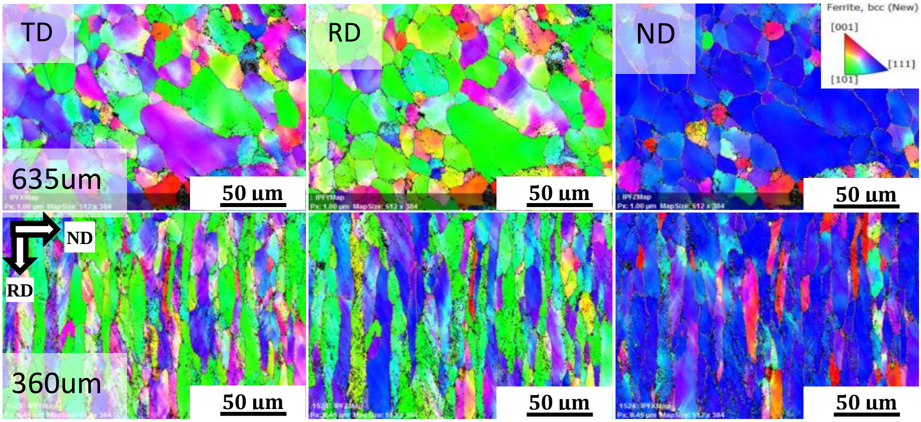
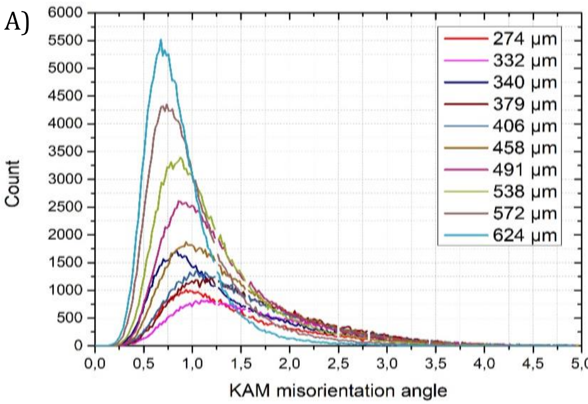


Figure 6.12 EBSD IPF Maps in different thicknesses

The selected crystallographic parameters effectively capture the microstructural evolution of the deformation in the investigated type of anisotropic steel. Due to the dislocation mechanism of deformation, the evolution and concentration of dislocation structures can be adequately quantified using the KAM distribution and the ratio of LAGB and HAGB presence. The dependencies are illustrated in the figure 6.13. The RGB method for the development of crystallographic texture rotation does not provide sufficient sensitivity to quantify the degree of plastic deformation and serves only as a descriptive parameter.



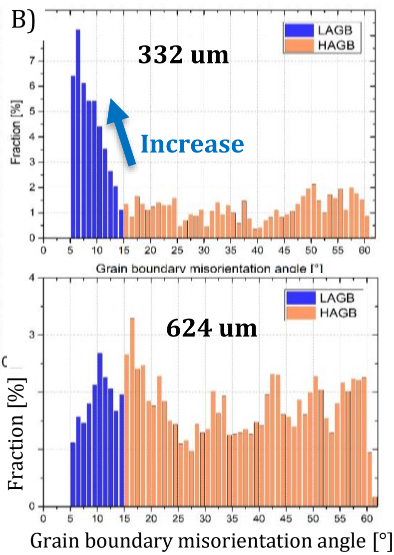


Figure 6.13 A) KAM distribution dependent on the thickness reduction; B) elevation of LAGB with increase of deformation

5.5 Effect of Metallurgical Quality on Plasticity

SEM and chemical microanalyses revealed the presence of inclusions in the form of titanium carbonitrides and aluminium-based complex oxides, with a significant predominance of TiCN content. Microcrack initiation occurs on these inclusions during the final stage of deformation, leading to failure as shown in Figure 6.14. In the case of the studied steel, the presence of microcrack initiation on these inclusions cannot be considered significant in terms of degrading plastic capacity of the steel. This is due to the limited area of occurrence, which is only in the region close to failure, and so it can be considered as the final state of deformation that has no effect on the previous plastic flow of the material.

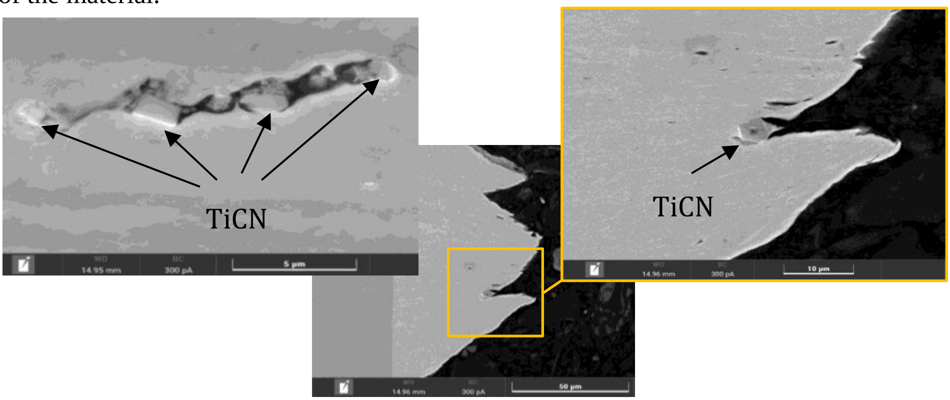


Figure 6.14 Microcrack initiation on present inclusions

6 Conclusion of Dissertation Thesis

Local thinning at critical positions of stamped parts is a complex problem with many influencing factors. The study focused on two key interrelated effects - the stress/strain state (in terms of major/minor strain ratio) and locally increased strain rates associated with the complex shapes of real stamped parts. Limit state analyses of stamped parts have focused on the evolution of deformation localisation at critical positions and the evolution and extent of strain hardening. For this purpose, graded strain states of real stamped parts up to critical thinning and failure were used.

A critical influence of friction at the interface between the forming tools and the sheet metal was identified. Friction restricts the plastic flow of the material away from the localised area, even in the presence of localised strain hardening. This contributes significantly to the location of thinning and the characteristic appearance of 'inhomogeneous' necking under uneven tensile stress. The restriction of plastic flow also affects the strain rate, leading to an increase in the deformation speed, which in turn affects the response of the material. Therefore, the effect of increased strain rates on the response of the analysed material was also investigated. Mechanical tests were carried out at selected stress-strain conditions and varying strain rates to monitor the development of graded microstructural deformation. The samples were then subjected to material analyses or non-destructive testing.

The following main conclusions can be drawn from the analyses and tests carried out:

- A process has been introduced to explain the formation of specific localised thinning at critical positions of stamped parts, which also captures the deformation characteristics from a microstructural perspective.
- Uniaxial tensile tests revealed a small anisotropy in mechanical parameters between the transverse direction (TD) and the rolling direction (RD), with a difference in the r-value of approximately 15%. A similar effect was observed in biaxial testing using hydraulic bulging, where an initial tendency for failure to initiate perpendicular to the TD was detected.
- Crystallographic analyses (EBSD) revealed a tendency for the crystallographic textures rotation under the influence of minor strain in the localized neck during uniaxial tension. Specifically, this resulted in a rotation towards the [111] orientation in the rolling direction (RD). The minor strain also affects the number of microcrack initiations at inclusions due to the increased deformation capacity under this type of loading.
- In the region close to failure ("fracture process zone"), all types of loading showed a tendency for the preferential [111] texture to decrease in the normal direction (ND), together with a rotation tendency towards [001]. In both the transverse (TD) and rolling direction (RD) there was a simultaneous tendency for the proportions of the preferential textures ([001], [111], [101]) to equalise due to significant grain deformation.
- The stress/strain mode of loading influenced the mechanical response of the material. Under plane strain conditions, higher strength values were recorded compared to conventional tensile testing, with an increase of approximately 50 MPa in yield

strength ($Rp_{0.2}$) and approximately 60 MPa in ultimate tensile strength (R_m). This suggests that conventional tensile testing may distort the actual mechanical response of the material for a given application.

- Strain rate clearly affects the mechanical response of the analyzed material across all tested stress/strain states. Both in uniaxial tension and under plane strain conditions, a significant increase in dynamic yield strength was observed, accompanied by lower strain hardening during plastic deformation.
    - In the case of uniaxial tension, this increase ranged from approximately 120 % to 180 % compared to the quasi-static response, depending on the strain rate;
    - in the case of plane strain, this increase was approx. 200 %.

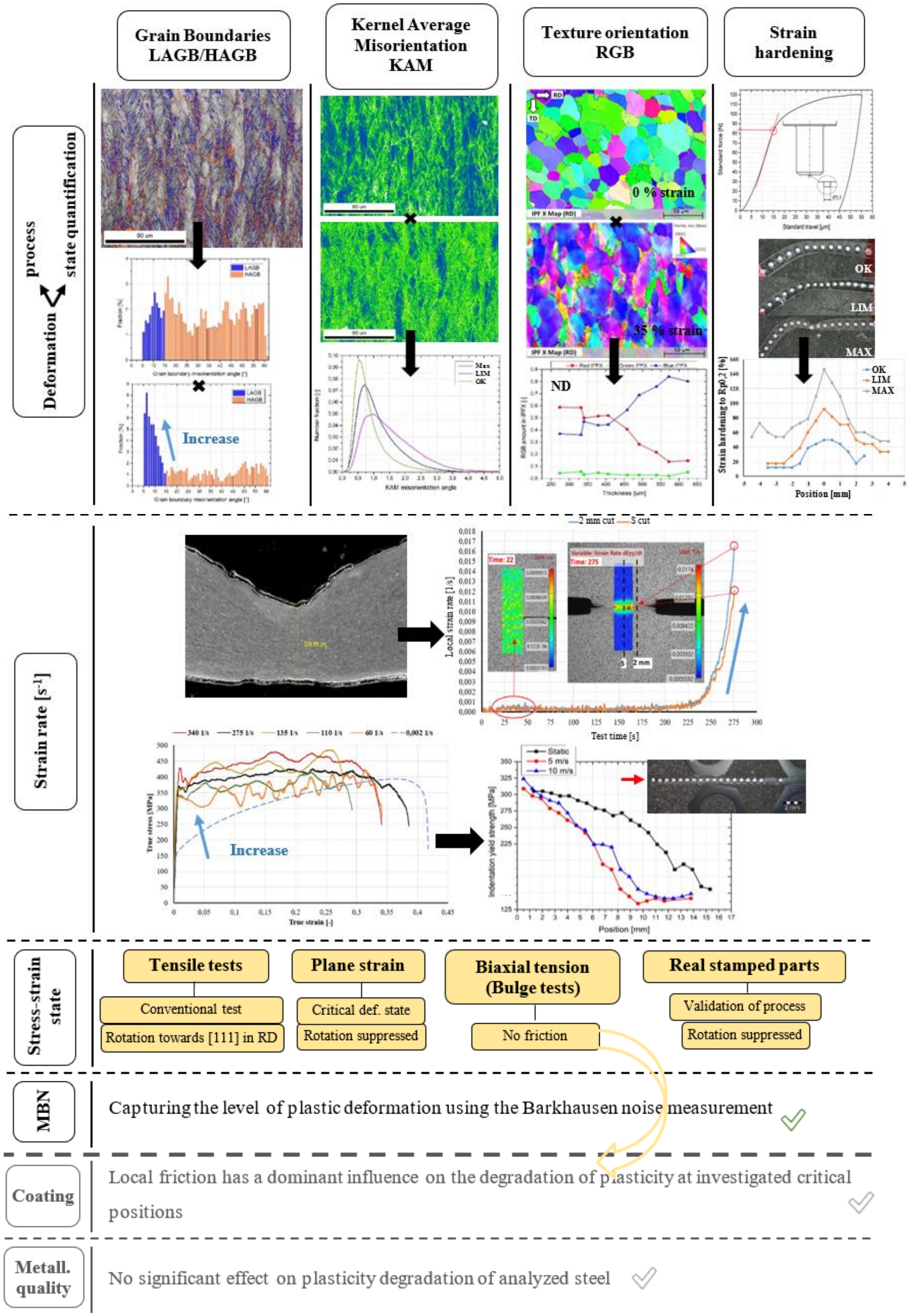
  This effect may negatively impact the distribution of plastic deformation in critical areas of stamped parts. In biaxial loading conditions, the influence of strain rate on deformation localization around the bulging apex was observed.

- Analysis of plane-strain conditions, or unconventional EWF specimens, showed a state close to the limit in stamped parts. Therefore, a simplified test for material deformation response at critical positions can be proposed. An increase in strain rate of 1-2 orders of magnitude was observed for localised deformation within a narrow band. This condition is similar to the critical positions in stamped parts where the strain rate increases, affecting plastic capacity and material flow.
- Parameters for quantitatively monitoring the degradation of plasticity were proposed: the proportion of Low Angle Grain Boundaries (LAGB) and Kernel Average Misorientation (KAM) distribution quantify the development of dislocation mechanisms, i.e., plastic deformation. For example, in stampings LIM (thickness 500 μm) and OK (550 μm), differences were observed in comparable areas as follows:
    - Proportion of LAGB: 0.45 (LIM) vs. 0.37 (OK), with a significant 50% increase in number of boundaries detected in LIM.
    - In the KAM distribution, a reduction in the maximum value of approximately 20% was observed at the same positions in the stampings. When comparing OK with MAX (thickness 270 μm), a reduction in the maximum value of up to approximately 50% was observed.
- The selected non-destructive method of Barkhausen noise measurement (MBN) enables the monitoring of plastic deformation development in the investigated steel.

- Analyses of metallurgical quality and microcrack initiation at inclusions on plasticity showed a minor influence for the analysed steel. Microcrack initiation occurs only in a narrow region around the fracture.

The analyses monitored the effects of stress/strain state and strain rate on the mechanical response of the analysed material and its microstructural deformation evolution. The results show a significant influence of both deformation type and strain rate, indicating that all these factors together influence the deformation behaviour at critical positions of stamped parts.

A comprehensive overview of the results and the relationships identified between the various analyses are graphically illustrated below.


Grain Boundaries LAGB/HAGB
Kernel Average Misorientation KAM
Texture orientation RGB
Strain hardening
Deformation process state quantification
Increase
0 % strain
35 % strain
ND
OK
LIM
MAX
Strain rate [s⁻¹]
2 mm cut
S cut
Local strain rate [1/s]
Test time [s]
340 1/s
275 1/s
135 1/s
110 1/s
60 1/s
0,002 1/s
True stress [MPa]
True strain [-]
Increase
Static
5 m/s
10 m/s
Position [mm]
Stress-strain state
Tensile tests
Conventional test
Rotation towards [111] in RD
Plane strain
Critical def. state
Rotation suppressed
Biaxial tension (Bulge tests)
No friction
Real stamped parts
Validation of process
Rotation suppressed
MBN
Capturing the level of plastic deformation using the Barkhausen noise measurement
Coating
Local friction has a dominant influence on the degradation of plasticity at investigated critical positions
Metall. quality
No significant effect on plasticity degradation of analyzed steel

7 Contribution of the Dissertation Thesis

The contributions of the thesis to both practice and theory are related. Most of the theoretical findings also offer practical benefits due to the need to capture ongoing processes in critical positions of stamped parts and to understand the various factors affecting material deformation. This is also crucial for subsequent integration with potential non-destructive testing applications.

From a practical point of view, the following can be considered beneficial, for example:

- Evaluation of the individual loading conditions presented on the resulting mechanical response and distribution of material deformation, excluding the effects of friction.
- Evaluation of the effect of increased strain rates under various stress/strain states.
- Description of the deformation localisation process in critical positions of stamped parts, with specification of the deformation evolution from a microstructural perspective.
- Verification of the possibility to monitor the degree of plastic deformation in real stamped parts using the selected non-destructive method.

From the theoretical point of view, the following can be considered beneficial, for example:

- Description of the deformation evolution from a microstructural perspective at defined levels of plastic deformation and under different stress/strain states, with reference to the graded deformation state of real stamped parts.
- Evaluation of the mechanism of localised deformation formation in critical positions of real stamped parts.
- Monitoring the development of microstructural deformation using selected crystallographic indicators.
- Evaluation of the impact of strain rate on mechanical response and strengthening in the analysed material.
- Verification of the detectability of deformation with differentiation of deformation states in the analysed steel using the Barkhausen noise measurement method.

8 Future research perspectives

During the dissertation work, several additional questions emerged regarding the analysed problem that define suitable follow-up work. These are aimed at refining and complementing the presented results with a focus on the used analytical methods. The key areas for further investigation include:

- Evaluation of deformation localisation in dynamic bulging tests near the bulging peak, including DIC measurements on samples at quasi-static strain rates. Correlation of results with deformation states of real stamped parts from simulations.
- Evaluation of Barkhausen Noise (MBN) measurements on graded plane strain and bulged specimens.
- Monitoring of deformation localisation at high strain rates in uniaxial tension using Digital Image Correlation (DIC).
- Design of new specimen geometries to investigate plane strain conditions to achieve higher plastic deformation with no crack propagation.
- Investigation of the extent of strain hardening and overall mechanical response across different geometries of tested tensile specimens at different strain rates - Investigation of the effect of specimen deformation length incorporating strain gauge measurements (including potential inertial effects due to impact which may influence deformation behaviour).

Authors Publications

[I] KLEJCH, F., SCHMIDOVÁ, E. (**2024**) “Limit State of Bake Hardened Stamped Interstitial-Free Steel Automotive Parts Caused by Local Thickness Reduction”, Periodica Polytechnica Transportation Engineering, 52(3), pp. 276–281.

[II] SCHMIDOVÁ, E., KLEJCH, F., SUNILKUMAR, M. R. (**2023**). Development of anisotropy and strain hardening in damaged stamped parts made of IF steel. Engineering Failure Analysis, 145

[III] SUNILKUMAR, M. R.; SCHMIDOVA, E.; KLEJCH, F. Microstructural Influence on Fracture Toughness of IF Steel and DP Steel. In: Journal of Physics: Conference Series. IOP Publishing, (**2023**). p. 012010.

[IV] KLEJCH, F., SCHMIDOVÁ, E., MEJTSKÝ, T. (**2022**). Anisotropy and Hardenability of Interstitial Free Steels Under the Influence of Localized Deformation. Applied Engineering Letters, 7(3), 125–131.

[V] SCHMIDOVÁ, E., NESLUŠAN, M., ONDRUŠ, J., TROJAN, K., PITOŇÁK, M., KLEJCH, F. AND RAMESHA, S.K. (**2021**), Monitoring of Plastic Straining Degree of Components Made of Interstitial Free Steel after Uniaxial Tensile Test by the Use of Barkhausen Noise Technique. Steel Research Int. 2100597.

[VI] KLEJCH, F. - SCHMIDOVÁ, E., Fatigue Strength Degradation of Thermomechanically Rolled High Strength Steels Welds, (**2021**) METAL 2021 - 30th Anniversary International Conference on Metallurgy and Materials, Conference Proceedings, pp. 391 – 396,

[VII] KLEJCH, F. - SCHMIDOVÁ, E. - VÁGNER, J. - ZETKOVÁ, I. Capturing of Uneven Deformations of Lightened 3D Printed Parts, Perner´s Contacts, (**2020**), vol. 15, no. 2, s. nestránkováno. ISSN: 1801-674X.

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** The author has also co-authored more than 20 technical reports related to the field of material engineering.*

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