Approaches to analysing scatter in forming simulations: from fundamental to pragmatic.

E.H. Atzema¹², M.E. Scholting¹ and M. Abspoel¹

¹ Tata Steel Research & Development, IJTC, PO Box 10000, NL-1970 CA IJmuiden, the Netherlands
² University of Twente, ET-NSM, PO Box 217, NL-7500 AE Enschede, the Netherlands

Eisso.atzema@tatasteeleurope.com

Abstract. Including scatter in material properties has received attention in the last decades but, it is not fully mature yet. Industry has cooperated with academia to progress the topic, but at the same time devised simpler ways to start analysis anyway. Robustness analysis is a pre-requisite for process optimisation. Tata Steel has been in material modelling for Sheet Metal Forming for many years and has developed its own yield locus model to enable better customer support. The accuracy of this Vegter model comes at a price, however: more parameters to be measured. Wiebenga devised a robustness analysis but it requires more input than is usually available. At the same time leading software vendors introduced options to evaluate statistical behaviour. Obviously, process optimisation is only useful when accurate models can be employed, so in this paper we will focus on how the scatter in material properties translates in scatter in yield locus for the BBC2005 model vs. Vegter 2017. Automated statistical analysis was not available for Vegter 2017. So, finally, to enable estimation of scatter in forming processes in the short term with Vegter individual simulations were done on a selected number of input datasets. This is shown to give markedly different results to BBC2005.

1. Introduction

Including scatter in material properties has received attention in the last decades but, it is not fully mature yet. A key issue is the interdependency of parameters [1][2]. Industry has cooperated with academia to progress the topic [3][4], but at the same time devised simpler ways to start analysis anyway [5]. Robustness analysis is a pre-requisite for process optimisation. This is because often, a deterministic optimum is on a boundary of the design space. In such cases any scatter will lead to approximately 50% out-of-spec products, which can hardly be called optimal. Robustness analysis can also be used to understand process failure not seen in deterministic analysis despite use of a safety margin [6].

Tata Steel has been in material modelling for Sheet Metal Forming for many years and has developed its own yield locus model to enable better customer support [7]. The accuracy of this Vegter model comes at a price, however: more parameters to be measured. In his work, Wiebenga [3][5] used the Vegter yield locus but had to find an alternative way to get the data needed. His work will be briefly summarised in section 2. He studied the material scatter of 41 coils of DX54D+Z forming steel. With so many parameters (17) describing the behaviour mutual dependency becomes even more of an issue. It needs to be accounted for as otherwise the resulting scatter is overestimated.
Earlier than Wiebenga, Abspoel [8] has been working on a pragmatic approach, where hardening and yield locus were treated independently. A DoE approach was used, and the mutual dependence of parameters was accounted for by not using the theoretical DoE point but finding the closest actual coil dataset. This will be briefly re-iterated in section 3.

At the same time leading software vendors introduced options to evaluate statistical behaviour. One example of that is AutoForm-$\sigma$, which will be used in this paper. Currently, Vegter 2017 is not available in AutoForm-$\sigma$, the next best option is BBC2005, which is. Because process optimisation is only useful when accurate models can be employed, in this paper we will focus on how the scatter in material properties translates in scatter in yield locus for the BBC2005 model as a representative of the Barlat family of models widely used in advanced analyses. This is then compared to the scatter as found using the Vegter model. It is found that the scatter prediction is markedly different, and the explanation is in the way BBC2005 is formulated (see section 4), which causes inaccuracies. Although the analysis is focusing on the BBC2005 in AutoForm, the findings apply to much of the Barlat family of yield loci, and to other software packages.

So, the fundamental route requires too much data to be practical today, and advanced yield models available in scatter modules of leading software contain substantial flaws. So, finally, to enable estimation of scatter in forming processes in the short-term in this paper authors have improved the pragmatic solution by basing it on Vegter 2017, that will be presented in the paper. In the longer term it is proposed to software vendors to make Vegter 2017 available in their scatter analysing modules.

2. Fundamental research
The mutual dependencies in parameters for constitutive behaviour have been examined by Wiebenga for 41 coils of DX54D+Z. For the full Vegter yield locus he used 13 free parameters, fixing the second stress component in the plane strain point at 0.6 times the biaxial point. For the hardening an additional 3 parameters and the thickness were chosen to scatter as well, totalling to 17 parameters.

![Figure 1 Parameter correlations, reproduced from [3]](image)

The measurement of the full Vegter criterion is labour intensive, which is not prohibitive in obtaining a representative data set for deterministic simulation but is too expensive to find properties for 41 coils.
So, Wiebenga relied on tensile tests to obtain uniaxial stress data in three directions, but for the other stress states he had to rely on CTFP texture-based yield locus modelling as published by An [9].

Reproduced from Wiebenga is Figure 1 showing the mutual correlations in the parameters for the DX54D+Z collective.

The impact of material scatter on the process was not directly done on the FE simulations. Rather a meta-model was derived from the simulations and Monte Carlo simulations done on the meta-model. For constructing the meta-model the FE simulations were run in multiple DoE points.

To run a full factorial Design of Experiments of simulations would obviously be prohibitively expensive. A way to solve the computational expense and realize the correlations between parameters is to replace the direct physical parameter set with a transformed orthogonal parameter set, in Wiebenga [3] this was done via Principal Component Analysis. Reasonable accuracy in describing material scatter could be obtained with 4 parameters. When analysing process sensitivity, however, more than 7 parameters were needed. This makes the analysis rather complicated not to mention that statistically significant amounts of data need to be gathered for all materials of interest.

As PC are orthogonal, setting up a DoE is now trivial. The modelling of the statistics was done with normal distributions, later work by Nejadseyfi [4] has extended this approach to non-normal distributions and an analytical derivation of the process scatter.

2.1. Discussion:

Obtaining sufficient input data for statistical modelling, especially of the yield locus, is not practicably feasible with mechanical testing. Using texture-based yield loci is introducing some inaccuracy.

Also, there are more sources of scatter than the material parameters, friction can be modelled quite advanced nowadays, but the large influence it has makes it highly likely that small variations in oil layer thickness also influence the process significantly [10].

The experimental validation of the method on the demonstrator product showed that a robust optimum had fewer rejects than a deterministic but not zero defects. So, the method was not accurate enough to really do without safety margin.

Care must be taken to ensure the most influential sources of scatter are considered. We deliberately say influential, not largest. Wiebenga showed in his thesis [3] that 95% of the scatter in material properties could be captured by 4 parameters. However, once the sensitivity of the process was added at least 7 parameters were needed [5]. The different constraints impose on the demonstrator process showed different sensitivity to individual parameters.

3. Pragmatic approaches

In the past we have published [5] some simplified approaches to capture the material scatter. There the hardening and yield locus were treated independently (based on observation of lack of correlation on multiple materials examined, Figure 2).

Scatter in process strains by scatter in the hardening in Abspoel 2011 was perceived to be realistic. However, scatter in process strains by scatter in the Vegter Lite yield locus seemed unrealistically high.

An alternative way to incorporate dependencies is to directly use all individual coil data sets in simulations. By employing only measured combinations of parameters we can be sure no fake scatter is introduced. This approach cannot be extended to analytical derivations of final scatter.

Also, the approach is limited to the coils for which the yield locus has been obtained, for instance by the CTFP model [9]. In the meantime, a method has been developed by Abspoel et al. [11] to construct Vegter yield loci from 3D tensile tests alone, Vegter 2017. Based upon decades worth of data, non-linear correlations could be found between all Vegter points on the yield locus and simple tensile test parameters. In [11] it can be seen that the model is quite accurately describing experimental data, but moreover the mechanical experiments for full Vegter are difficult to carry our correctly and it is highly likely that the Vegter 2017 is more accurately describing the material than a measured full Vegter, because it is averaged over so many materials that test noise becomes negligible.
4. Material modelling

The material model consists of hardening and yield locus which are assumed independent, and isotropic hardening is used. Before we treat what scatter has been applied in individual cases some general principles are discussed. Tata Steel has long been an advocate of physically based hardening laws as promoted by Bergström and adapted by Vegter & van Liempt [12]. These are generally employed in FE simulations as tabulated data because the analytical law is usually not available.

It should be noted that most of these analyses have been performed with strain rate sensitivity by the additive Krabiell-Dahl equation, also mentioned in [12]. The additive model has its roots in physical metallurgy, unlike the often-employed multiplicative law which is wholly empirical. Adding strain rate sensitivity makes a crucial difference in the onset of necking as already shown in [13] for FLC and [14] for implication in forming and crash. Although thorough characterisation of strain rate sensitivity over tensile test to crash test range (more than 4 decades: 0.0067 – 200 s⁻¹) is expensive, in [14] it is shown that an ordinary tensile test with a short burst at higher strain rate (factor 10) suffices in practice. This is because to have strain rate sensitivity in the simulations in the first place is more important than to get the parameters determined very accurately.

Initially, only hardening will scatter, keeping yield locus and FLC (i.e. “formability”) constant, then yield locus will scatter, still with constant FLC. Finally, in scrap rate analysis the scatter in FLC is also considered. In this paper damage and fracture are not considered, but for AHSS the damage may influence the onset of necking and as such scatter in damage tolerance should also be taken into account.

4.1. Case 1a Hardening only, stylised

Initially, only the hardening was varied. This choice was motivated by the need (mentioned in the introduction) to have accurate models so BBC2005 would be often chosen for the yield locus. In BBC2005 the plane strain points and shear points are given implicitly and as average over all directions through definition of the exponent m, often referred to as m-value (Figure 5). Since it is implicit it is not easy to see how m should be varied to account for material scatter. It can be expected that many users therefore will simply not vary it.

The hardening was varied based on the stylised high-low-average approach also used in [8] where based on strength (both Rp and Rm) the 5%, 50% and 95% percentiles in the tensile test data were chosen from the collective and individually fitted to the hardening law. This will underestimate the scatter somewhat, see Figure 2. Rp and Rm do not correlate 100%. So, it is possible that some coils have lower Rp but higher Rm than others, meaning they also have some more hardening.
4.2. Case 1b Hardening only, sampled
Instead of using high-low-average one can also use fitted hardening data on the extremes selected in section 4.3, this includes not only strength variation but also hardening scatter. So, for the hardening this means a more randomly selected approach. It is reasonable to assume the sampled data points also cover the scatter in hardening reasonably well.

4.3. Case 2 Yield locus Vegter 2017
Secondly, the yield locus was varied, based on Vegter 2017 (Figure 3). This takes only tensile test data (but in three directions) and consequently of some grades the steel industry has data available for many coils from many production runs. Possibly, the advanced data processing of Wiebenga could be applied, but the correlations that will be found in the PCA will be those pre-programmed in by using Vegter 2017. Somehow, this did not seem to make much sense.

Treated in much more detail in [11] here it suffices to say that shown in Figure 3 are:
- The uniaxial points and r-values are taken from tensile tests
- The biaxial point is governed by all uniaxial points and their r-values.
- The plane strain points are governed by the associated uniaxial point and the biaxial point
- The shear points are governed by both associated uniaxial points and their r-value.

Figure 3 Principle of how Vegter 2017 controls plane strain, shear and biaxial (each point individually)

Instead of doing PCA, some extremes were sought from the data set in terms of mean $r$ ($\bar{r}$) and $\Delta r$ as well as in mean plane strain point vs. its $\Delta$. The latter is plotted in Figure 4. The small blue dots represent the entire data set, the plus symbols a selection of extreme properties for the simulation set. This is not a statistical method but should still serve to give a good impression of how large the scatter in strains is resulting from material property scatter. Future work would be to adapt the statistical methods such as employed by Wiebenga [5] and Nejadseyfi [4] to these models and obtain a truly statistic representation of the process scatter resulting from material.

Finally, for analysing the effect of only scatter in the hardening an average yield locus should be derived from the dataset. In Figure 4 the big open circle is the average yield locus, it was defined as in the middle of the scatter of $\bar{r}$ and $\Delta r$, but in mean F$_{ps}$ vs. $\Delta F_{ps}$ plot it can be seen it is skewed to one side. Fruit for thought when one aims to define a truly average yield locus.
4.4. Case 3: Yield locus BBC2005

Finally, the comparison between Vegter 2017 and BBC2005 yield loci was done. As stated above this was motivated mainly by the availability in automated statistical simulations of the BBC2005 model, and lack of availability in the same of the Vegter 2017.

As also stated in the introduction, the most accurate models will be chosen for meaningful scatter analyses, and for AutoForm-σ the best option is BBC2005. The recommendation in the manual of AutoForm R8 is to use m=6 for steel. As said in case 1, it is not trivial how to change it, and scatter in m is useful only when scatter in plane strain points is known. The scatter in the biaxial point will often also be unknown, but since we have that available here (from Vegter 2017) the choice was made to use it, to get the best possible results from BBC2005. The biaxial point can also be automatically generated by the software from Hill48, or Barlat models. For the sampling points these are shown in Figure 6 where it is evident that both alternatives scatter more than Vegter. In Table 1 this is quantified, the standard deviation (for the 20 sampling points) is twice as large for Barlat than it is for Vegter 2017. Hill is two and a half times larger again, but not a realistic option for accurate simulations anyway.
Table 1 Scatter in biaxial point for different models.

|                | Fbi Hill | Fbi Barlat | Fbi Vegter |
|----------------|----------|------------|------------|
| Min            | 1.22     | 1.01       | 1.13       |
| Max            | 1.42     | 1.13       | 1.18       |
| Average        | 1.32     | 1.10       | 1.15       |
| Standard deviation | 0.066   | 0.027      | 0.014      |

5. Simulation exercise
The sensitivity of each process to material scatter is likely to be different. But to demonstrate the impact of accounting for different parameters scattering an AutoForm R8 simulation of simple hemispherical punch stretching was performed as a demonstrator, Figure 7. This may or may not translate well to other processes, but it gives us an illustration of effects. Moreover, the lack of complicated shape makes the effect of material model more prominent.

From each simulation the maximum major strain has been chosen and the strain combination of that point is plotted in an FLD. This is not the same point for all simulations, some fail in diagonal direction and others in transverse direction, and the distance from the centre varies as well. But it is representative of practice in that failure of a process is governed by the weakest link.
5.1. Case 1: Hardening
The solid symbols in Figure 8 are the results for the stylised hardening, the plus symbols represent the sampled hardening. Both with average Vegter yield locus. The predicted scatter is larger in case 1b but still in a narrow band compared to the solid points presented in the next section. Moreover, they stay on the same strain path, indicating that failure is probably in (nearly) the same point, and that strain ratio is governed by yield locus rather than hardening.

5.2. Case 2: Vegter 2107
The results of the sampled points in terms of yield loci and hardening behaviour is shown in Figure 8. The scatter of the strains is much larger than with hardening alone, it leads to the conclusion that scatter in the yield locus has a much larger influence than scatter in the hardening. At least for this forming steel in this test. Also, the extra scatter is in the ratio of the major and minor strain and not in the magnitude of the (equivalent) strain.

5.3. Case 3: BBC2005
Again, the use of strain rate sensitive material behaviour is advocated, and the impact of using it will be clear from Figure 9. The open symbols represent the effect of strain rate sensitive behaviour which is absent in the solid symbols. Furthermore, BBC2005 yields higher strains and is therefore predicting the process to be more critical than Vegter 2017. What also is seen is that the scatter cloud for the BBC model is smaller while the Vegter model shows a wider cloud. Comparing this to the situation of the hardening variation only, it suggests that the averaging of the plane strain points in the different directions in the BBC model with only one parameter is filtering away the scatter in this plane strain point directions. And thus, has a damping effect on the scatter.

6. Estimating scrap rate
As shown above, robustness analysis is possible. However, authors feel it is not mature enough yet to do quantitative predictions of scrap rate. For this, more aspects of the process scatter will have to be added, and more validation of the current treatment of the material properties is needed. But to evaluate the effect of different models a rough estimate of the scrap rate has been made.

In the previous section the maximum strain in the product was plotted for various models and multiple coils. One aspect missing from that approach is that the FLC is also scattering, more formable coils have a higher FLC. Authors have chosen to include the FLC in the estimate of scrap rate. Comparing BBC2005 with Vegter 2017, both with and without strain rate sensitivity a difference in predicted scrap rates can be estimated. From the set of extremes that were simulated in section 5. It can be calculated how many are above (their own individual) FLC based on [15] and used as indicator of scrap rate. This is not statistically sound obviously, but it does give an impression, see Figure 10.
The product simulation was critical for the intended draw depth, and for more clarity three shallower depths are plotted. The trend is clear: in the simulation BBC2005 is more critical than Vegter 2107 and adding strain rate sensitivity makes the process less critical.

In our view BBC 2005 yields more critical simulation because of the lack of accuracy in (mainly) the plane strain points. The base models are well validated (Vegter 2017 [11] strain rate sensitivity [14]), but admittedly for robustness the experimental evidence is yet to be gained. This requires quite some effort, obviously. Authors are confident that implementation of Vegter 2017 and strain rate sensitivity in the automated robustness modules like AutoForm-σ, PAM-opt (and similar for other software vendors) is the way forward.

![Figure 10 Estimation of scrap rate at different draw depths](image)

7. Conclusions

- In the problem analysed here, the yield locus scatter has a (much) larger influence than the hardening scatter.
- Although the models employed have been validated in the past in a deterministic manner, the statistics of scatter have yet to be validated in practice.
- Reliable scrap rate statistics are not available yet.

8. Future work

The strong sensitivity to yield locus may be due to the examined material: a forming grade low carbon sheet steel, which is highly textured. In the future the implications of material scatter for HSLA and AHSS could be evaluated with the same pragmatic method.

A first attempt towards validation could be to acquire material left over from release testing and performing the stretch test on a (large) number of coils. Validation on a real production part requires large stamping runs and consequently is not something the steel industry could do in-house but should seek cooperation with one of its customers.

An estimation of trend in scrap rate can already be made, but since the base is not a random selection of data points this therefore is statistically inadmissible. Past efforts from academia to provide a solid statistical foundation should be applied to the current method.

Models as accurate as possible should be used and software vendors are called upon to make Vegter 2017 and additive strain rate sensitivity available for their statistical modules. The method used in this paper is labour intensive and analysis of robustness would benefit greatly if this was automated. Although the evaluation was simple in the test product, and this could equally simply be done for complex products, insight into how to cure any robustness challenges is difficult to obtain. Visualisation of local scatter on the product as provided by e.g. AutoForm-σ is crucial here.

In future more subtle effects such as strain path change and evolving yield loci could also be added to the scatter analysis, where the main challenge will be to obtain the relevant parameters.
References

[1] Gerlach J., *Sensitivity and Robustness. Analysis for Quantification of the Influence of Material Scattering*, in: Forming Technology Forum 2007 – Application of Stochastics and Optimization Methods, IVP, ETH Zurich, Switzerland, 14th – 15th March 2007.

[2] Eisso H. Atzema, Pascal Kömmelt, *Modelling Parameter Interdependence in Stochastic Simulations of Stamping: Hardening*, in: Forming Technology Forum 2007 – Application of Stochastics and Optimization Methods, IVP, ETH Zurich, Switzerland, 14th – 15th March 2007.

[3] Jan Harmen Wiebenga, *Robust design and optimization of forming processes*, PhD thesis University of Twente, 2014, Enschede, the Netherlands.

[4] O. Nejadseyfi, *Robust Optimization and Tailoring of Scatter in Metal Forming Processes*, PhD thesis University of Twente, 2019, Enschede, the Netherlands.

[5] J.H. Wiebenga, E.H. Atzema, Y.G. An, H. Vegter, A.H. van den Boogaard, *Effect of material scatter on the plastic behaviour and stretchability in sheet metal forming*, J. Mater. Proc. (214) p 238-252.

[6] Sigvant, M., 2006, *Influence on simulation results from material and process scatter*, Proceedings of IDDRG 2006 conference, Porto, Portugal.

[7] Vegter, H. and van den Boogaard A.H., 2006, *A plane stress yield function for anisotropic sheet material by interpolation of biaxial stress states*, Plasticity 22,(3), p 557-580.

[8] Michael Abspoel, Marc Scholting, Eisso Atzema, *Characterisation and modelling of the stochastic behaviour of deep drawing steels*, in: Forming technology Forum 2011, May 17-18, 2011, ETH, Zurich Switzerland.

[9] Yuguo An, Henk Vegter, Louisa Carless, Marc Lambriks, *A novel yield locus description by combining the Taylor and the relaxed Taylor theory for sheet steels*, International Journal of Plasticity, Volume 27, Issue 11, 2011, Pages 1758-1780, ISSN 0749-6419, https://doi.org/10.1016/j.ijplas.2011.05.003.

[10] J. Lacues, C. Pan, J.-C. Franconville, P. Guillot, M. Capellaere, T. Chezan, J. Hol, J.H. Wiebenga, A. Souchet, V. Ferragu, *Friction and lubrication in sheet metal forming simulations: Application to the Renault Talisman trunk lid inner part*, in: Proceedings of International Deep Drawing research Group (IDDRG) 2019, 4-7 June 2019, Enschede, the Netherlands.

[11] Michael Abspoel, Marc E. Scholting, Marcel Lansbergen, Yuguo An, Henk Vegter, *A new method for predicting advanced yield criteria input parameters from mechanical properties*, J. Mater. Proc. (248) 2017, p 161-177, http://dx.doi.org/10.1016/j.jmatprotec.2017.05.006.

[12] Vegter H, Mulder J, Liempt P van, Heijne J. *Work hardening descriptions in simulation of sheet metal forming tailored to material type and processing*. Int. J. Plasticity 2016; 80; 204-221. Vegter & van Liempt Tailored hardening.

[13] CHLJ ten Horn, *FLC benchmark*, Proceedings of the 7th International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes, September 1- 5, 2008, Interlaken, Switzerland.

[14] M Abspoel, M E Scholting, M Lansbergen, *Thermomechanical forming and crash simulations*, Proceedings of International Deep Drawing research Group (IDDRG) 2019, 4-7 June 2019, Enschede, the Netherlands.

[15] Abspoel M., Scholting, M.E. & Droog, J.M.M., *A new method for predicting Forming Limit Curves from mechanical properties*, J.Mater.Proc., Volume 213, Issue ,May 2013, Pages 759–769.