A pragmatic strategy to take into account metal materials scatter in FEA

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Summary:

Since years, FEA tools have allowed to reduce development time of products. Main improvements have been done in hardware and software leading to the possibility of finer mesh and complete models of complex structures. In parallel, material science did strong efforts to develop material models able to take into account accurately anisotropy, strain rate sensitivity, failure and damage. These give to FEA methodology sufficient maturity to run DOE in a robust design approach. One of the main inputs is the material properties and associated scattering from production which can not be avoided.

Automotive industry has also become a global worldwide business. Same cars can be produced on several continents with different local suppliers of raw materials. Some slight changes in material properties can occur for a given metallurgical family depending on local material standards.

However, only few researches have been done yet on scatter modelling, which is still crucial for designers to assess quickly the reliability of their design.

We present here a pragmatic and economic approach to take into account material scattering in Finite Element Simulations with the example of flow curve according to the change of basic mechanical properties for metals. Good partnership between metals suppliers and carmakers is key for success. The output is a set of flow curves ready to be used as an input of optimizing FEA software.

Keywords:

Metal materials scatter, flow curve, metal supplier partnership

1 Introduction

The methodology presented in this paper aims to provide a set of flow curves representing accurately the mechanical properties scattering of a given metal material whether according to the material specification or according to the results of statistical analysis of basic mechanical properties (Rp0.2; Rm; A%). The best way to obtain information about mechanical properties scatter is to establish a close cooperation with the material supplier. Often considered as sensitive information from the supplier point of view, it is a real benefit for customers to better represent the material in finite element simulations to finally assess the robustness of the final product. Indeed, mechanical properties scattering can not be avoided and is a result of the complex material making process.

Meinhardt and al [1] present a robustness study of an industrial stamping process. From the technical point of view, commercial software are now available to make automatic several simulation runs with different input data. Input variables are listed and among others material scattering is of main importance. About 150 flow curves were computed to represent the material scattering. However, it is not detailed how the material data were obtained, modeled and if any correlation was found between mechanical properties parameters.

Lainé and Kayvantash [2] remind the important number of simulation runs to get a correct confidence level on the analysis response. In this approach, the material was modeled using well known hardening equations (Hollomon, Johnson-Cook, Krupkowski). Due to the difficulty to assess the material scattering, input parameters were adjusted according a mean value and a standard deviation based on 100 in-house tensile tests. In addition to the cost of the tests, one can not guarantee that these 100 tensile tests represent the all range of mechanical properties variation. Also, it was not investigated whether mechanical properties were correlated to each other, which could reduce drastically the necessary number of runs.

Atzema and Kömmelt [3], as material supplier, highlight that mechanical properties obtained from tensile test are not independent from one another. The spread in each as obtained from a series of tensile test must be related before they can be used as stochastic input to simulations. They also remind that the cut off on mechanical properties distribution due to material rejected for not fulfilling specifications must be taken into account while running normality tests. Finally, the question is opened about which material characteristic could be assumed constant over all coils of a certain grade.

This work aims to give part of the answer to the open questions listed before. The methodology is illustrated with a Dual-Phase steel sheet having minimal yield strength of 980 MPa. This grade has the particularity to be made through a complex process including cold rolling and partial quenching which makes it as one of the most complex sheet steel to produce for the supplier. Therefore, it is expected to observe a large scattering on mechanical properties. Lüders plateau effect is almost not visible which simplifies the analysis. This effect will therefore not be investigated in the present discussion.

2 Methodology

The methodology is illustrated in Figure 1. Two types of input data are needed. The first one is a tensile test out of a sheet issued from a random coil out of the material supplier production, run by the supplier's customer. The second one is a set of data provided by the material supplier containing as many as possible results from tensile test done in the production plant. Indeed, in order to check the coil conformity versus specifications, the supplier makes one or several tensile test. In general, Rp0.2; Rm and Axx% (the reference length for A% will depend of the material standard) are reported on material certificate since these properties are the ones defined in material standards. The main philosophy is to combine both input data. The tensile test curve gives information about work-hardening behavior (or hardening rate θ, equation 1), presence of eventual Lüders Plateau and information on the ratio Ag / Axx% whereas the production data set (Rp0.2; Rm and Axx%) gives the spread of mechanical properties. It is important to make sure that the tensile test done by the customer is done in the same conditions and if possible on the same test piece type than the ones conducted by the material supplier to make both input types comparables.

$$\theta = \frac{d\sigma}{d\varepsilon} \qquad \text{(Equation 1)}$$

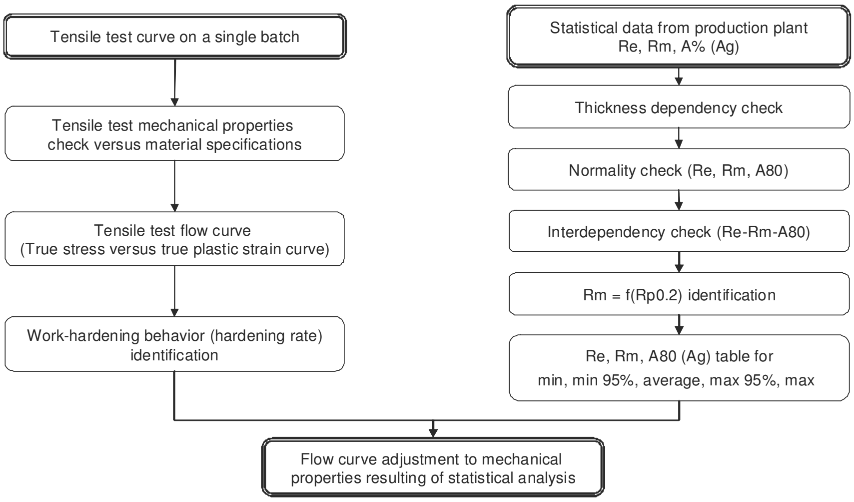

Fig. 1: methodology flow chart

2.1 Statistical analysis of production data

In this example, the supplier was able to provide about 1500 datasets in a table format. Figure 2 illustrates the 9 first data sets. Available information for a given grade are the coil number, the test piece position versus rolling direction, the heat number, nominal thickness and basic mechanical properties. The thickness covered was ranging from 0.5 to 2.1 mm.

Coil Nr.	Position	Heat	Nominal Thickness	Rp0,2 (MPa)	Rm (MPa)	A80 (%)
C66923	transversal	250862	0.50	954	1117	7
C66924	transversal	250876	0.50	971	1121	7
C68491	transversal	250876	0.50	975	1087	8
C38220	transversal	243855	0.70	866	1038	7
C74509	transversal	252474	0.70	952	1101	7
C26661	transversal	698420	0.70	928	1113	7
C82527	transversal	253600	0.70	986	1130	7
C55992	transversal	535055	0.70	987	1165	7

Fig. 2: data provided by material supplier (9 first lines shown out of about 1500 in total)

2.1.1 Thickness dependency check

The first analysis consists in checking if the mechanical properties exhibit a significant variation according to thickness. If yes, part of the material scattering can be explained by this simple aspect. If only a specific thickness is intended to be used for part design, only the data corresponding to this specific thickness can be selected for the subsequent analysis. It is the analyst decision to consider or not the thickness dependency if detected. Figure 3 shows the plot of Rp0.2, Rm and A80% versus thickness. It can be observed that at thickness lower than 1 mm the material shows a tendency to a yield strength increase while the tensile strength seems to keep constant. In order to confirm, F&t statistical tests comparing variance and means are used to compare populations having thickness lower and higher than 1 mm. The tests results confirm same variance and different mean for yield strength; but also for tensile strength and A80%. This means there exist a statistically proven dependency to thickness.

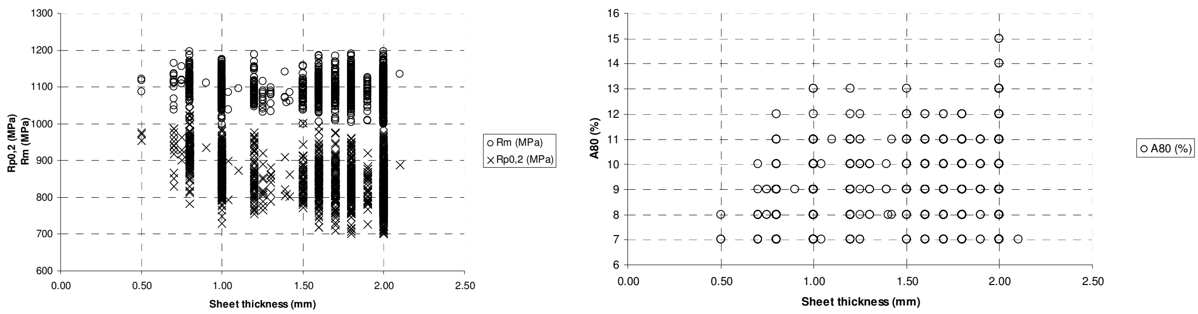

Fig. 3: Mechanical properties dependency versus thickness

A proposal to visualize the results in a convenient way is to use the box-plot representation (Figure 4). It confirms the highest thickness dependency with Rp0.2 and A80% and a lower one with Rm. Note that for A80%, an additional decimal digit would give more proper results. It will also be discussed later the sense to give to Axx% for flow curve purpose. Information on Ag would be more appropriated. In the subsequent analysis, only 2 mm thickness data sets will be considered, being still enough datasets (about 600) for analysis.

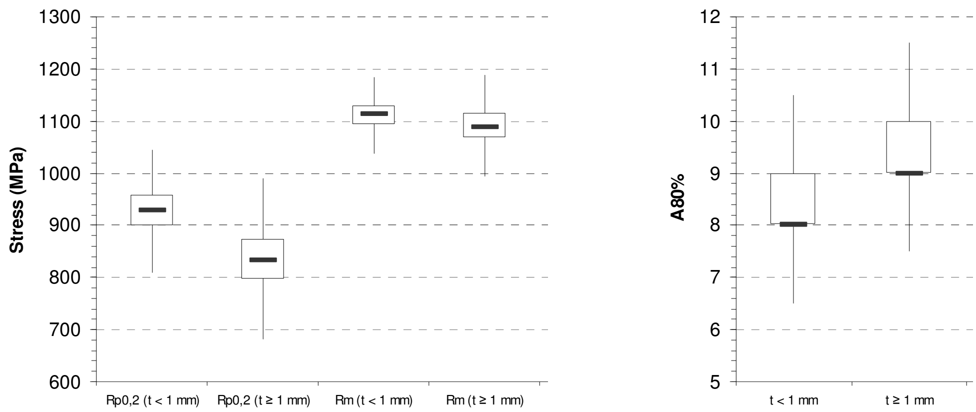

Fig. 4: Box-plots representation of mechanical properties dependency to thickness

2.1.2 Normality check

First thing to check before conducting statistical analysis is the normality of data distribution. If verified, the population can easily be modelled with a mean value and standard deviation. Classical normality tests are used like Anderson-Darling, Kolmogorov and Khi2. Distribution and Gaussian curve are presented in Figure 5.

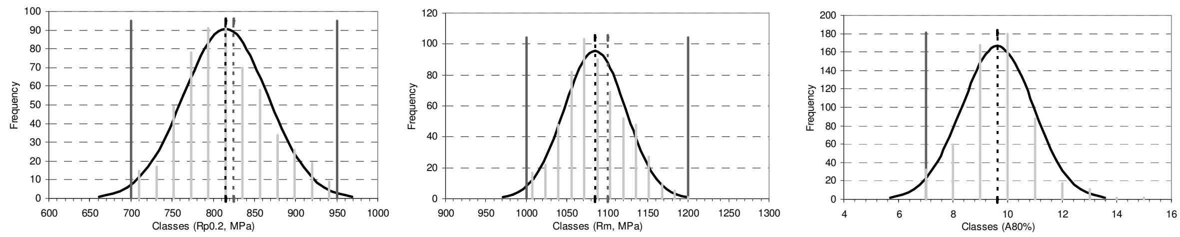

Fig. 5: Rp0.2, Rm and A80% distribution, Gaussian curve and specification limits

All tests rejected normality for the all three mechanical properties. For Rp0.2 and Rm, it is due to the fact, as mentioned by Atzema and Kömmelt [3], that a few coils not fulfilling specifications are rejected, which explains the chopped off distribution. Same phenomenon can explain the normality rejection for A80%. Also for A80%, 2 coils were found having A80% = 14% and two others having A80% = 15% which is still in the specifications but out of the Gaussian. Some measurements matters might explain it. However, classes tend to show a frequency in good agreement with a Gaussian curve. Therefore, from a pragmatic and engineering point of view, the distribution normality is accepted. Note that the average values of production for Rp0.2 and Rm are close to match the medium specifications, which is synonymous of a well controlled production process. Statistical analysis of A80% also allows defining higher statistical limit which is not defined explicitly in the material specifications. Finally, statistical results are presented in table 1. It can be seen that Rp0.2 exhibits higher scattering than Rm, not only due to the difficulty to measure Rp0.2 but also due to Rp0.2 definition itself and physical reasons from process, not discussed here.

	Rp0,2 (MPa)	Rm (MPa)	A80%
Mean	815	1084	9.63
Standard deviation	51	37	1.31

Table 1: Statistical results

2.1.3 Interdependency check

Taking advantage to get data as shown previously in Figure 2, it is possible to study interdependency of mechanical properties, which is a step further in the approach. Indeed, does it make sense to associate the lowest Rp0.2 values with the highest Rm one and vice-versa? Figure 6 shows a 3 dimensional plot of Rp0.2 (X axis), Rm (Y axis) and A80% (grey scale). X and Y axis are ranged at the material specifications limits.

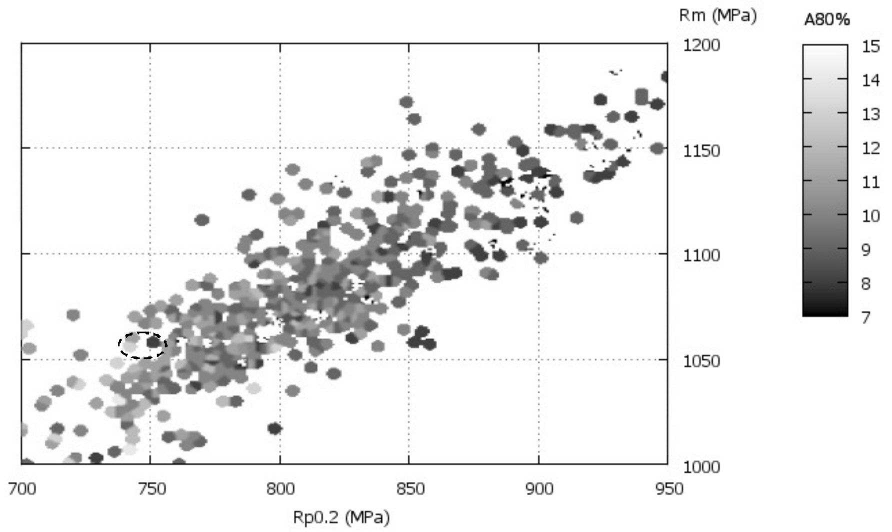

Fig. 6: Rp0.2, Rm and A80% interdependencies

A clear link appears between Rp0.2 and Rm. The tendency between [Rp0.2, Rm] and A80% is also visible and in agreement with what is usually known for metal materials: ductility tends to decrease when yield and tensile strength increase together. A detailed analysis of Rp0.2 versus Rm is proposed hereafter. The discussion is however still opened on the significance to give to A80%. In figure 6, an ellipse highlights particular points having almost the same Rp0.2 and Rm values but opposite A80% values. What would be the corresponding uniform elongation for those points? Is A80% scatter representative of Ag scatter knowing that total elongation values are partially driven by damage theories? For the purpose of this study, the assumption it is will be done. Therefore A80% distribution will be used as information for minimum, average and maximum values to give to Ag with additional information from in-house tensile test (Ag / A80% ratio). Figure 6 also shows that from the statistical point of view, some Rp0.2-Rm-A80 combination have no probability to happen.

2.1.4 Rp0.2 - Rm interdependency

Rm will be modelled as a linear function of Rp0.2 as given by equation 2. Mean and standard deviation values for Rm are already obtained from Table 1. In this stage will be defined a Rp0.2 mean and standard deviation corresponding to a reduced Rm range.

$$Rm = a.Rp0.2 + b$$ *(Equation 2)*

In order to characterize statistically Rp0.2 versus Rm dependency, Rm results from figure 5 are used. 3 classes of interest are selected: the one showing the highest frequency (1072 MPa), and 2 additional ones showing medium frequency (in this case 1040 and 1136 MPa were of choice). This choice is decisive for the final results and special attention has to be paid that the data sets of the selected classes do not interfere with lower and higher limits of yield strength, which would mistake the subsequent analysis. Figure 7 gives a graphical representation of the selected classes. The class range in this study is 16 MPa. Key assumption is that a difference of 16 MPa on Rm is not of significance on crash or forming simulation result. Note that in that case the class width is large enough to contain enough points for the following analysis. For other examples, reduced Rm range definition could be a compromise between analysis accuracy and reliability.

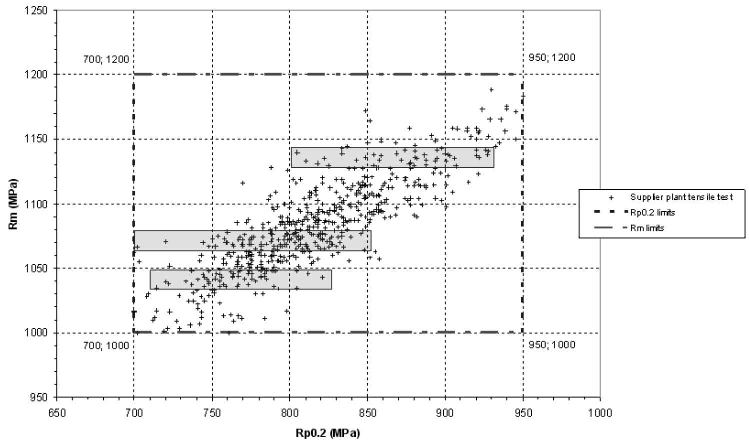

Fig. 7: Selected Rm classes and corresponding Rp0.2 for analysis

For each datasets of the selected class, a normality test is conducted. In this case, they are all positive whereas for a global Rp0.2 analysis including the 600 datasets, it was not. This demonstrates that considering the 600 datasets normality was rejected due to cut-off at specification limits. As the 3 classes were carefully selected, they do not interfere with Rp0.2 limits, which give to normality test a positive result. Results are presented in figure 8 and table 2.

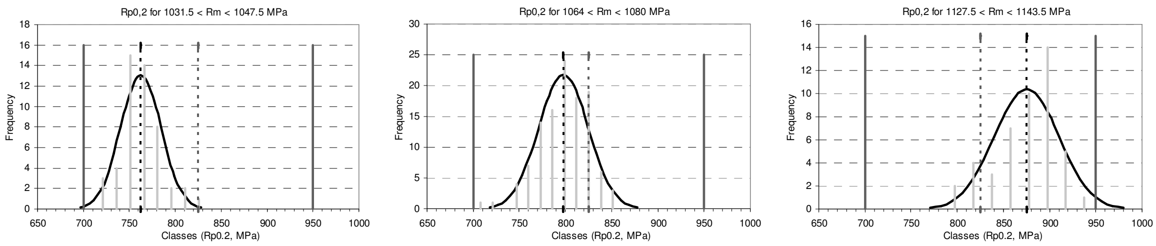

Fig. 8: Rp0.2 distribution for several Rm classes

	1031.5 < Rm < 1047.5	1064 < Rm < 1080	1127.5 < Rm < 1143.5
Rp0.2 Mean	762.5	798	875
Rp0.2 Standard deviation	22	26.6	34.9

Table 2: Rp0.2 mean and standard deviation according to Rm classes

Observing the 3 plots of Figure 8, one can observe again the increase of Rp0.2 with Rm. Standard deviation is also increasing and is the result of the material itself but also dependant of the classes choice done previously. It is not aimed to find any physical reason to explain it in this paper. However, it seems more conservative to consider the highest Rp0.2 standard deviation (34.9 MPa) for the following of the analysis and it is still possible in a more complex model to include all the available information. Note that this value is still lower than the one considering the all datasets population as given in Table 1.

Mean values from table 2 are used to identify a and b parameters from Equation 2. Plotting mean Rm versus mean Rp0.2 for the 3 selected classes and a linear tendency curve, the following result is found (equation 3) with a correlation coefficient of 0.996 which validates the hypothesis of linearity.

$$Rm = 0.8498 Rp0.2 + 392.8 \qquad \textit{(Equation 3)}$$

A direct conclusion of this result is that an increase of 1 MPa for yield strength does not correspond to 1 MPa increase for tensile strength but about 0.85. This will have a influence on the choice of the approaches described in § 2.3. At this step of the study, the Rp0.2 – Rm population is completely modelled thanks to Equation 3, Rp0.2 standard deviation for a given Rm value (Table 2) and Rm results from Table 1.

2.1.5 Table of mechanical properties for flow curves

A proposal is given as shown in Figure 9 for coordinates of interest to build flow curves. Grey areas represent the coordinates of probability 0, e.g. coils which will never be produced if the supplier keeps the same process than the one studied here. Vertical Gaussian curve represents Rm distribution. Horizontal ones represent Rp0.2 distribution according to Rm. Point n°1 is the most probable coil to be received at customer's. Points 2 and 3 represent the most probable Rm with corresponding deviation (95 % confidence level) on yield strength. Points 5 and 8 represent higher and lower Rm (95%) at nominal yield strength. Points 4, 6, 7 and 9 give the yield strength deviation of points 5 and 8. Finally, points 10 and 11 are the material specifications limits. Note that points 4 and 9 have been given specifications limits for Rp0.2. These 11 points coordinates represent a table to be used in the next steps for building flow curves. According to FEA needs, any other flow curve can also be built.

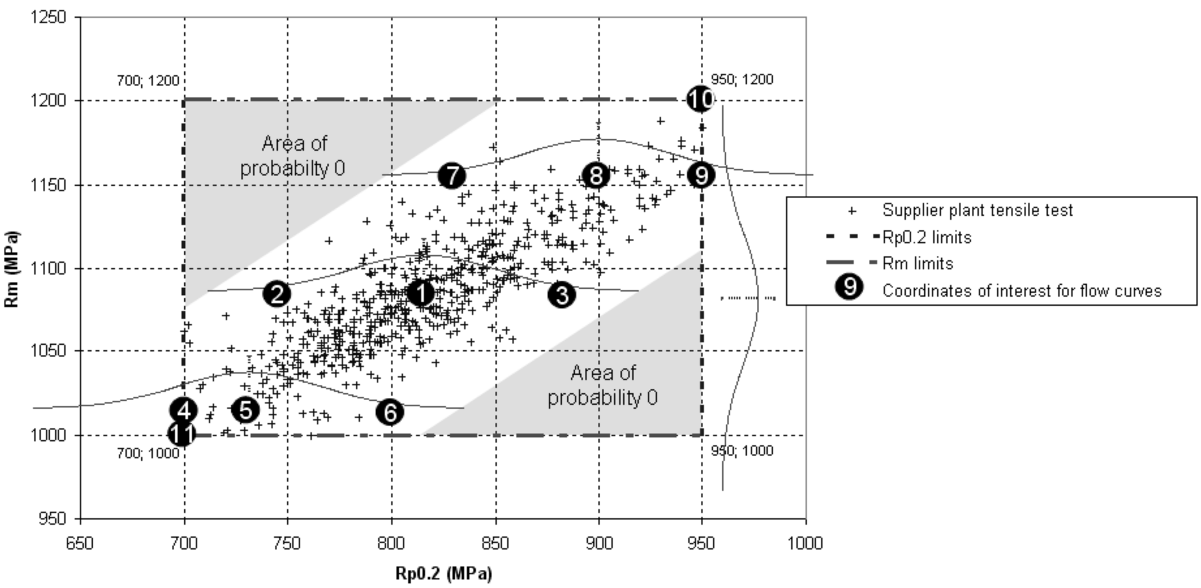

Fig. 9: Coordinates of interest at 95% of confidence level and specification limits

2.2 Tensile test on a single material batch

Second input data of the methodology is the result of a tensile test conducted out of a coil (or sheet as coil sample) randomly chosen by material supplier. The tensile test results should include the engineering stress-strain curve, mechanical properties as listed before (Rp0.2, Rm, Axx%) and also implicit but precious information Ag. Indeed, until now only Axx% was known. The tensile test shall also be done in the same direction compared to rolling and if possible same testing conditions than the ones for production data. Some slight changes in testing strain rates could however be admitted as long as it remains in the range defined by standard defining quasi-static tensile test.

Of course it is expected that this random coil mechanical properties obtained through this tensile test match the cloud of points obtained through production data. It does not matter wherever the Rp0.2-Rm point is located in the cloud of figure 9.
From this tensile test, true stress versus true plastic strain curve is computed. Then, work hardening behaviour is identified using equation 1. Key assumption of the methodology is that the result of equation 1 is almost a constant whatever the Rp0.2-Rm-Axx% is and is a characteristic of the metallurgical family and the global tensile strength level. Figure 10 represents several engineering stress-strain curves of several metallurgical steel families. Considering separately each family, the curves can be considered almost parallel to each others which validates the hypothesis of constant work-hardening behaviour in a given grade. Figure 11 presents 4 engineering curves of DC06 grade covering almost all the range of Rm specification. Applying a vertical translation on each curve to match the average Rm value, one can superimpose the curves in a satisfying way. It can also be noted on this figure the scattering on A% compared to uniform elongation Ag.

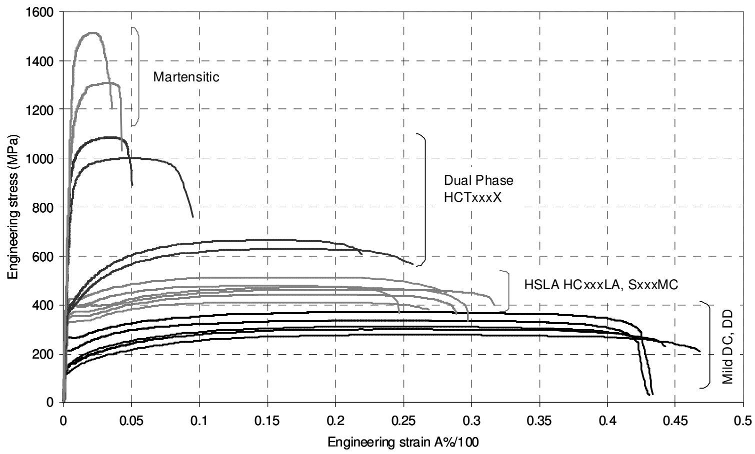

Figure 10: Ilustration of iso work-hardening behavior per metallurgical family through engineering tensile curves

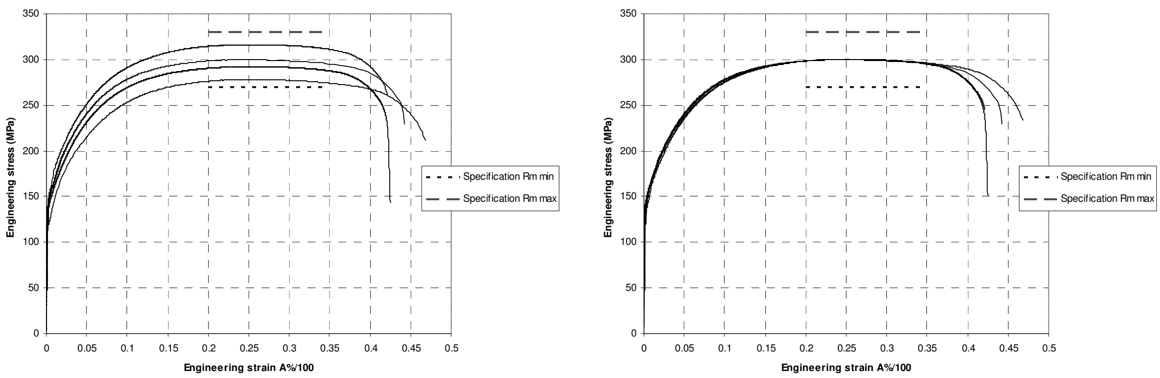

Figure 11: superposition of some DC06 steel tensile curves applying vertical translations only

2.3 Application to scattering correction on flow curves

Two approaches are suggested to derive from a tensile test curve the flow curves at mechanical properties defined in Figure 9. The first one is to apply vertical translation to match the desired tensile strength value and eventually an horizontal translation to match the yield strength value. However, this approach is limited by the fact that it is sometimes impossible to reach both Rm and Rp0.2 targeted values.

The second one is to use a predictive model having as input Rp0.2, Rm and Ag and giving as output the flow curve. Such a model was developed by the author for the purpose of this study but can not be presented in details in this paper. Model ability to reproduce accurately the material work hardening behavior was verified first using the tensile test results of §2.2. Then the same model was used to compute flow curves at coordinates defined by Figure 9. Uniform elongation values were obtained considering Ag/A80% ratio obtained from the tensile test curve and A80% distribution in Figure 5. Final results are presented in Figure 12 with the curves numbering corresponding to Figure 9.

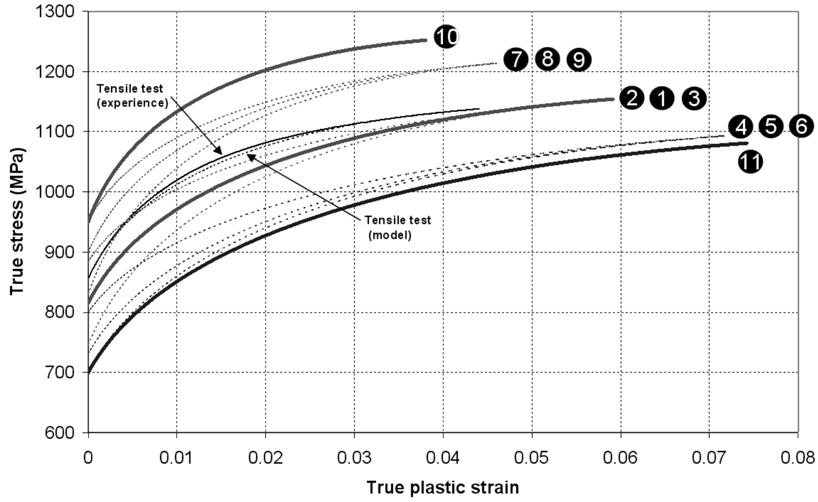

Fig. 12: flow curves modeled according to figure 9.

2.4 Methodology validation & discussion

In order to validate the methodology, some tensile test curves from tensile tests done in production plant (Figure 13) were used and compared to the result of both statistical model and flow curve predictive model. Results of §2.1.4 were used to define corresponding Rp0.2 at +/- 95% confidence level having Rm as input. Results are presented in Figure 14.

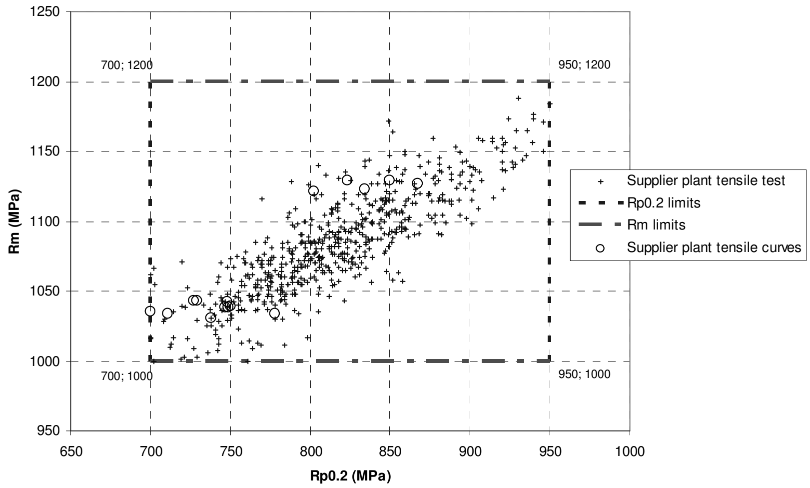

Fig. 13: coordinates of tensile curves from production plant

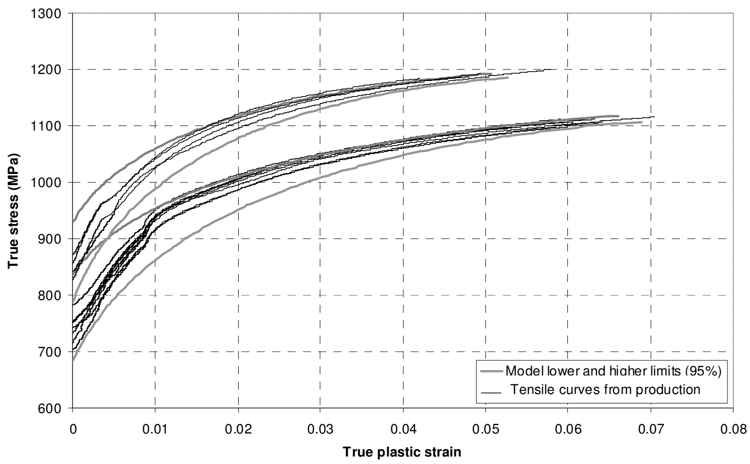

Fig. 14: Model results versus tensile curves from production

It can be observed a good agreement between model and experience. Some slight overstress can be seen and explained by two factors: the first one is the change of strain rate during tensile test in the plant conditions which influences directly the stresses. This effect occurs between 0.005 and 0.01 plastic strain. The second factor is the fact that the scattering of Ag for a given tensile strength is not taken into account yet, for the reasons mentioned before, and could have an influence in the shape of the curve according to the predictive flow curve model developed.

3 Summary

The methodology presented in this paper, applied to quasi static flow curves modelling, aims to answer the basic needs of designers and FEA engineers using metal materials for automotive products: which material is the most suitable according to the given technical requirements and how will mechanical properties scatter affect the product behaviour? It also takes into account the economical and time constraints that face material department of any automotive industry company.

To give the highest quality answer in a fast and economic way, the methodology is based on two aspects: the first one is the use of production data from the metal supplier plant: the basic mechanical properties Rp0.2, Rm and A% which are the ones defining materials in standards. Applying the basics of statistical analysis, it is possible to highlight interdependency between mechanical properties, which reduces the number of flow curves possibilities. A simple statistical model linking Rp0.2 and Rm is proposed with associated average and standard deviations. However, the link between uniform elongation Ag and total elongation A% is still an open point to take into account elongation scattering.

The second one is the use of a quasi static tensile test, which allows checking the material from a mechanical and metallurgical point of view. The highest interest for the methodology is to catch the material work-hardening behaviour or hardening rate, e.g. the tensile test curve shape. Once this parameter is known, two strategies are presented to derive the flow curves at any possible value of Rp0.2, Rm, A% : applying vertical and horizontal translations or using a flow curve predictive model having as input the previous mechanical properties.

Finally, a master set of flow curve can be computed, representing the material behaviour at the limits of its specification, at the average level of production and at 95% of minimum and maximum confidence level. It then allows running a few FEA calculations and eventually a surface response for further analysis, depending of the subsequent FEA strategy.

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