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From Breakdown Rolling to Cup Testing – Integral Through-Process Texture Modeling of AA5182

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Abstract

A through-process modeling study of texture development for AA5182 sheet production from hot rolling through cold rolling and annealing is reported. The thermomechanical process model was coupled to physics based microstructure models for deformation texture (GIA), work hardening (3IVM), nucleation, and recrystallization texture (StaRT). The simulations were run prior to any texture measurements, thus the results were fully predictive. The model overpredicts the Cube texture during hot rolling but properly predicts the terminal texture after multiple cold rolling with intermediate annealing. With a new concept of yield locus prediction the final predicted texture was fed into a FEM simulation of cup drawing, leading to good agreement with the measurement.

1. Introduction

The final goal of the collaborative European research project VIR[FAB] was to develop microstructure based predictive models for processing and resulting properties of aluminum sheet connecting casting (VIR[CAST]) and final sheet forming (VIR[FORM]) [1]. The development of a predictive physics based through process model of texture evolution from hot forming through final annealing was a central part of the project.

Generally, the need for microstructural modeling is borne by the fact that microstructure rather than overall chemical composition determines material properties. Microstructure comprises the local distribution of crystal defects and chemical elements and is defined on a much smaller scale than conventional engineering dimensions. Microstructure, however, is not an invariant of a specific material. On the contrary, microstructure changes considerably during processing. Hence, the state variables of materials properties are defined on a microstructural level rather than macroscopically. Therefore, in order to predict the impact of a change of the processing route on materials properties, the microstructural evolution has to be simulated through the whole processing chain and has to be connected to the macroscopic scale for engineering property predictions.

Through-process modeling (TPM) of materials, therefore, requires a twofold integration, namely a horizontal connection of the processing steps and a vertical connection of physical models of microstructure development to the engineering scale.

In aluminum sheet production crystallographic texture was identified as key issue governing the resulting sheet properties. Hot rolling and cold rolling with (inter-)annealing are the processing steps where significant texture changes occur and where the final texture can be influenced to achieve the desired material properties. To test the performance of the present through process physical model, an industrial plant trial of sheet production of AA5182 was conducted. It is stressed that the simulation was run before experimental results became available. Hence, the results presented are truly predictive. As the ultimate goal of the simulation the predicted final texture was fed into a new concept of yield locus prediction to model cup drawing.

The paper describes the modeled process, then gives short introductions to the microstructure models and explains their horizontal and vertical assembly to a TPM. Finally, the results are compared to experimental data, which became available after the simulations.

2. The Modeled Process

The material was processed according to the typical industrial processing chain for commercial aluminum sheet as given in Figure 1. After casting and homogenization it was subjected to multipass break-down rolling in a reversing mill and then transferred to a three stand tandem mill for hot rolling and coiling. Finally, it was cold rolled in four passes with two intermediate annealing treatments and one final annealing. Samples were taken after breakdown rolling, hot rolling and the single cold rolling and (inter-)annealing steps. The mechanical properties of the final sheet were tested in directional tension tests and cup drawing. The simulation started with tandem hot rolling and took the transfer slab material as input. This owes to the fact that the overall texture after break down rolling is usually very weak and does not influence the subsequent texture development. This was the case here, too.

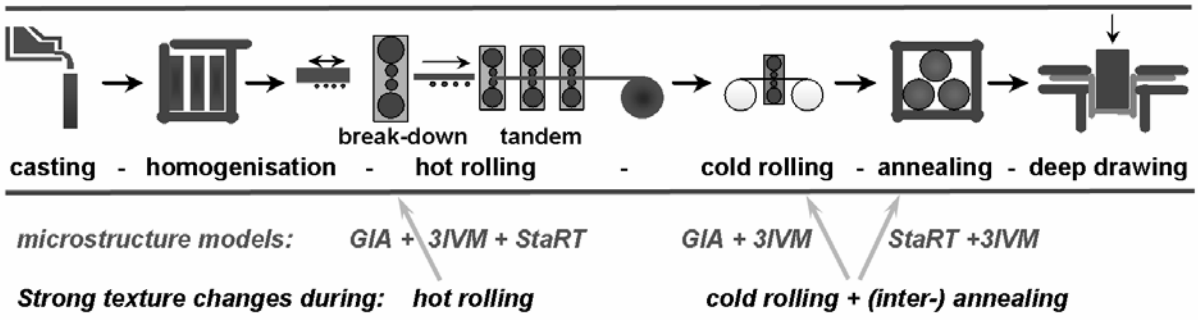

Figure 1: Typical processing chain of aluminum sheet. The texture determining steps and main applied microstructure models are indicated

3. Microstructure and Texture Models

Work hardening and softening was simulated with the dislocation based model 3IVM. It was used to predict the flow curves at a given temperature and strain rate for a specific material, characterized by composition, solute level, particle size, grain size, and texture. Secondly it was applied for simulating recovery during interpass times and annealing. The basic principles of the model are given elsewhere [2,3]. In variation of the basic version solid solution hardening was explicitly introduced into the current version of the model [4] (Figure 2). After having calibrated the physical parameters of the model to a specific flow curve it must be able to predict a flow field, i.e. the stress-strain behavior of a material in a

wide range of deformation temperatures and strain rates, accounting for changes of microchemistry (solute level, phase distribution), of course. Figure 3 gives the predicted and measured flow curves of AA5182 in the temperature range 300°C ≤ T ≤ 500°C, and strain rates 10^{-1}/s ≤ $\dot{\varepsilon}$ ≤ 10^{1}/s.

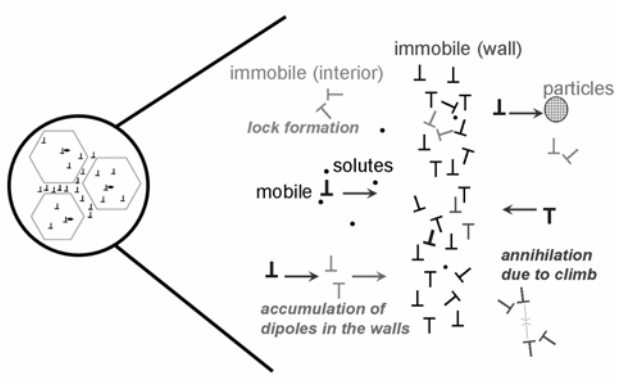

Figure 2: Principles underlying the work hardening model 3IVM. The dislocations form a cell structure. Mobile dislocations interact with other dislocations, impurity atoms, and particles.

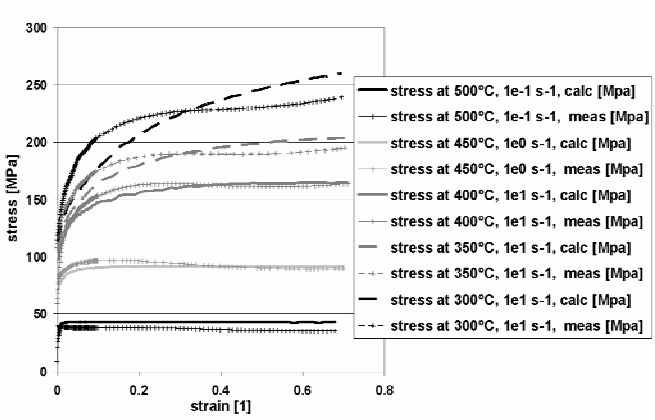

Figure 3: Measured and predicted flow field for AA5182 in the range 300°C ≤ T ≤ 500°C, 10^{-1}/s ≤ $\dot{\varepsilon}$ ≤ 10^{1}/s.

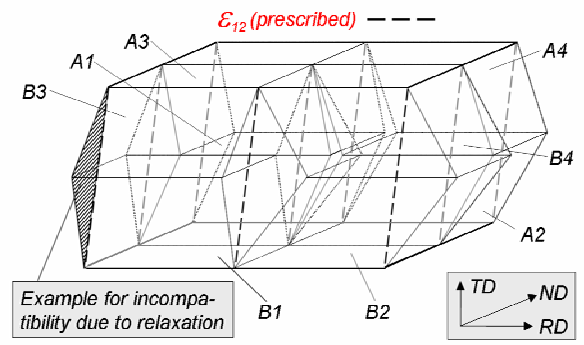

Figure 4: Principle of the GIA deformation texture model. The clusters consisting of eight grains (A1 to B4) internally undergo a free deformation but comply with the imposed deformation ε_{12} as a whole. Incompatibilities at boundaries are compensated with GNDs.

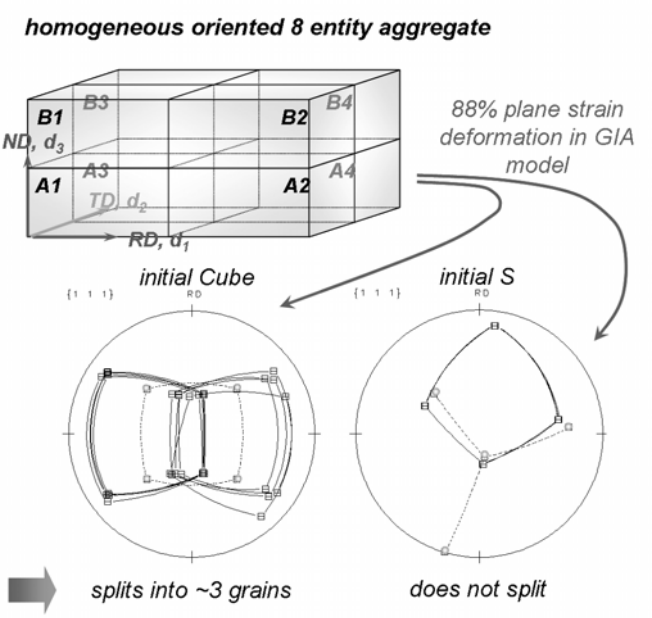

Figure 5: Divergence analysis of 2 major texture components with the GIA-Split-Up model.

The rolling texture was simulated with a grain cluster texture model (GIA) that takes grain interaction into account. Details are given elsewhere [5,6]. After discretization of the starting texture into 4000 orientations these orientations were randomly grouped into clusters of 8 grains. Each 8 grain aggregate had to comply with the externally imposed shape change but was allowed to internally partition additional shears among each other (Figure 4). Violation of compatibility at grain boundaries was compensated by geometrically necessary dislocations (GND). The local slip distribution was obtained by minimization of the total energy, comprised of GND energy and expended work of deformation. These energy terms depended on strength (flow stress), elastic constants, grain size and grain shape. Therefore, temperature and strain rate effects were implicitly taken into account [7]. At elevated temperatures aluminum is known to deform by octahedral as well by non-octahedral

slip. The contribution of non-octahedral slip systems depends on temperature and strain rate and can be predicted explicitly with the method described in [8].

The GIA model was also used for an assessment of nucleation sites and nucleation frequencies in recrystallization. For this purpose, the grain clusters were investigated with regard to orientation stability, which can be related to nucleation in stable orientations (Cube bands), and with regard to their divergence, which reflects the tendency to form deformation inhomogeneities (transition bands, Figure 5). Furthermore, the GIA model provided information on stored deformation energy (orientation and strain path dependent), orientation dependent recovery (ODR) rates and the tendency for the formation of shear bands. Details of the simulation of nuclei spectra with the GIA model are given in [9,10]. Analytical functions were defined to predict the number of nuclei contributing to the different nucleation processes [11]. This provided the nucleation texture for the StaRT model, establishing an essential link to enable a fully predictive TPM.

The recrystallization texture model StaRT is a time resolved but space averaged growth model. It distributes the recrystallization nuclei according to criteria given by the GIA model in the deformation texture components [12]. During each time step conditions were left free to change, e.g. the growth rate due to concurrent recovery, micro growth selection or nucleation rate. Also impingement of the growing grains was taken into account according to Avrami [13]. The growth rate of the grains depended on misorientation and local stored energy (associated with the amount of slip accumulated during deformation provided by GIA), and processing conditions, like temperature schedule.

In principle, microstructure will be considerably affected by phase transformations like precipitation. In AA5182, however, microchemistry is known to change very little from hot working through cold rolling. Thus, changes of microchemistry were not taken into account in the simulation, although respective models were available [14,15].

4. Linking the Microstructure Models to a TPM on a Macroscopic Scale

The implicit FEM code Larstran/Shape served as a thermomechanical process model. In order to improve the FEM predictions, the FE code was interactively linked to the 3IVM for work hardening and a full constraints Taylor model for fast Taylor factor prediction which served as an input to the 3IVM (Figure 6a). From the initial conditions (preheating temperature, transfer slab texture, grain size, solute and precipitate data) and the known rolling schedule this FEM package computed the temperature distribution in the rolled ingot during the processing history and the local deformation on the FEM mesh. During interpass and annealing times, the FEM package was employed for pure thermal calculations, in which an Avrami-type recrystallization kinetics model and the 3IVM computed the recrystallized fraction concurrent to the recovery of the material in post processing (Figure 6b).

The 2D-FE mesh comprised 10 elements through the half-thickness of the ingot (Figure 7). For elements close to midplane (S = 0.2) and close to the surface (S = 0.8) the texture was accurately modeled after each rolling pass with the GIA model taking the FEM data as input. In case of interpass recrystallization or during the annealing treatments the recrystallization texture was simulated with the StaRT model, including the nucleation analysis with the GIA model. Subsequently, the texture was fed back to the FEM to simulate the next rolling pass. The distribution of the new center and surface textures onto the FE-mesh is shown in Figure 7. The whole coupling strategy is depicted in Figure 8.

The target prediction was the texture after the terminal anneal. The terminal centre and surface textures were averaged to one integrated texture. With the respective Taylor factors of this texture under uniaxial tension in 0°, 45° and 90° to the rolling direction and under compression along the normal direction, the respective flow stresses were predicted by the 3IVM. These four values served as input to a yield function embedded in the FE code Larstran/Shape, which was employed to simulate a cup drawing test.

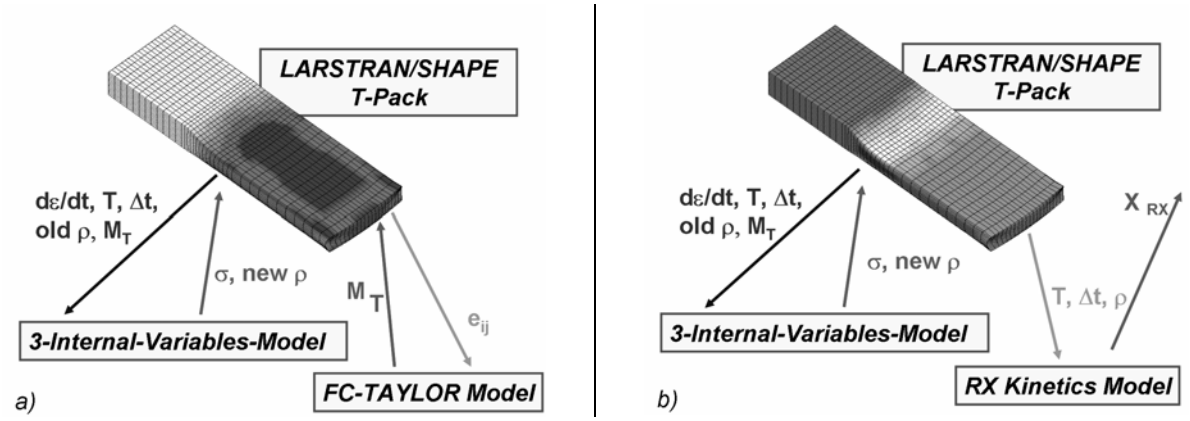

Figure 6: (a) Thermomechanical (FEM) process model during deformation. The 3IVM work hardening model and a simple Taylor model for Taylor factor calculation (needed for 3IVM) are integrated into the FEM code. (b) Pure thermal FEM calculation during annealing/interpass times. To account for the influence of recovery on the recrystallization kinetics the 3IVM computes the recovery in each element and time step, and an Avrami type recrystallization kinetics model based on dislocation densities as driving forces calculates the recrystallized fraction.

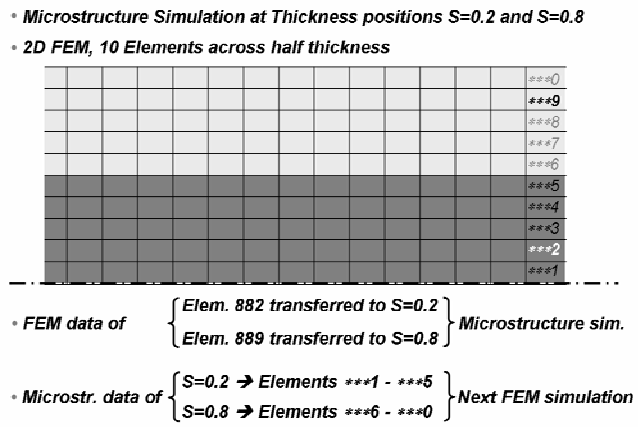

Figure 7: 2D FEM grid of half sheet thickness. Only elements ***2 close to the center plane and ***9 close to the surface of the rolled sheet were considered in this study.

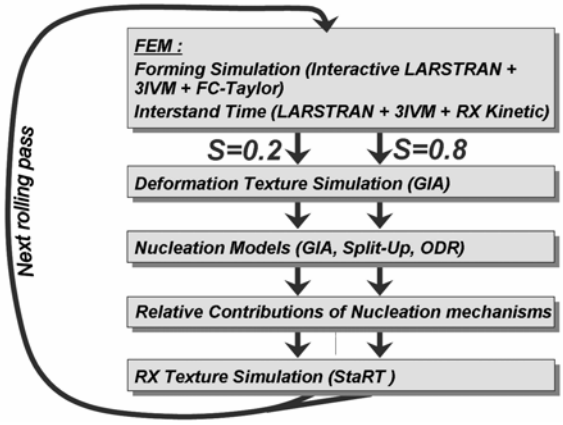

Figure 8: Coupling scheme for one deformation – annealing sequence.

5. Results and Discussion

The TPM generated numerous outputs such as macroscopic rolling forces, strain and temperature distribution etc. or local microstructure data like dislocation densities for each processing step. We will focus on the predicted midplane and surface textures of the hot strip and after the final annealing. Additionally, the predicted mechanical properties of the final product will be shown, since they are of most interest in industrial production.

For an easy comparison with experiment the textures are represented in form of volume fractions of the main texture components. Figure 9a shows that the Cube texture was strongly over predicted in the midplane of the hot strip, while the rolling components Brass-, Copper- and S-orientation were under predicted. At the surface (Figure 9b) Cube was underestimated. Usually AA5182 hot strips show much weaker surface than midplane Cube-textures. This trend was predicted too strongly by the TPM and also not observed experimentally in the present case (compare Figure 9a and 9b).

The TPM textures of the annealed cold rolled sheet (Figure 9c, 9d) demonstrated that the differences between simulation and experiment faded out with repeated cold rolling and annealing (see as well Figure 11). The impressive agreement of the terminal texture both at sheet center and surface plane is, of course, to a certain extent fortuitous. One reason seems to be the randomization (general decrease of texture intensity) of the texture during cold rolling and (inter-)annealing. While this is the cause for the disappearance of the over predicted Cube intensity, it is noted, however, that for a given set of conditions in terms of materials properties, like nucleation and growth rates of recrystallization nuclei and work hardening behavior, it is just as difficult to arrive at a random as a sharp texture.

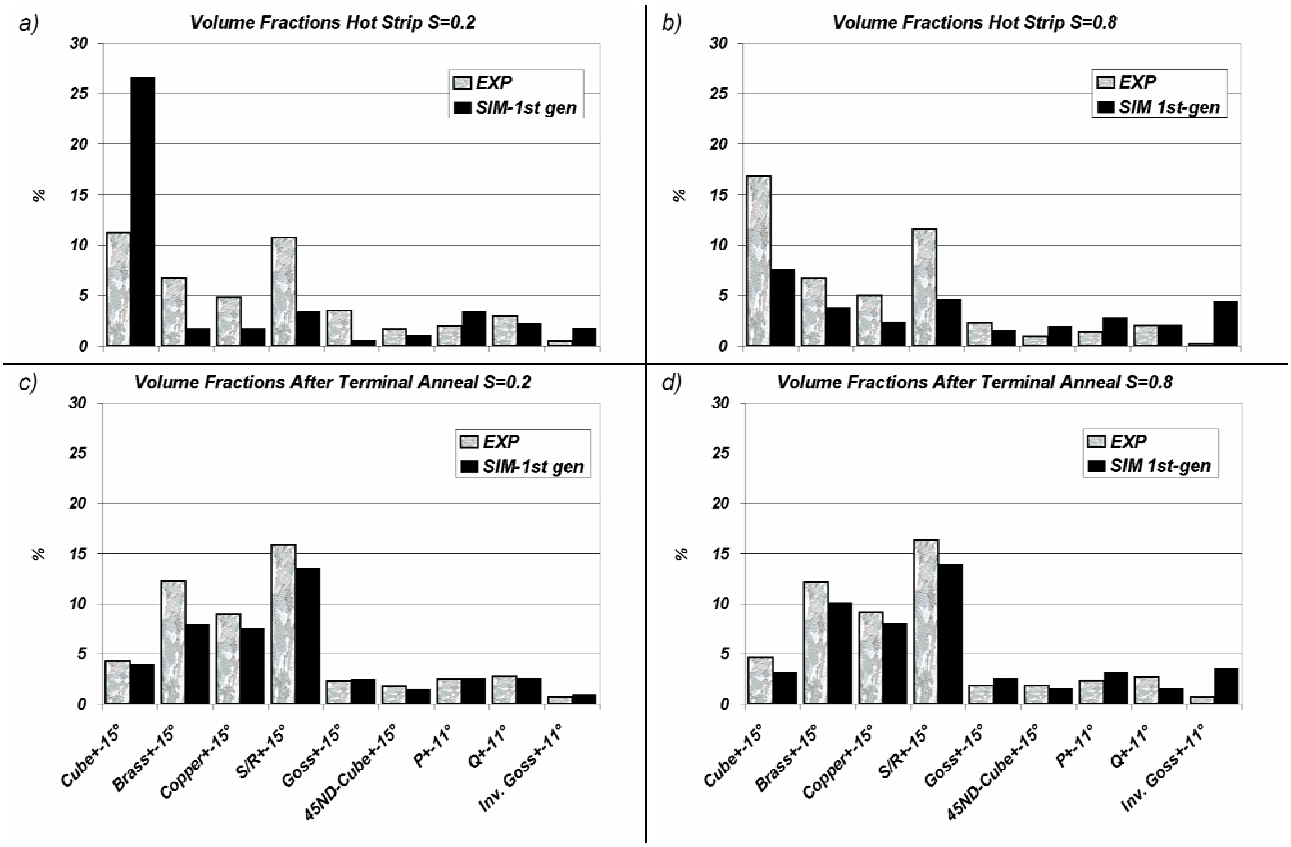

Figure 9: Predicted and measured textures in the hot strip (a,b) and after the terminal anneal (c,d), separately for the sheet center (S = 0.2, (a,c)) and the sheet surface (S = 0.8, (b,d)).Texture is represented by means of volume fractions of the main texture components indicated in diagrams (c) and (d), together with the assumed angular scatter of each component.

As explained above, the terminal texture and dislocation densities were used to predict directional flow stresses with the 3IVM. Table 1 shows the good qualitative agreement of flow stress for uniaxial tension in different in-plane directions with respect to the rolling direction. The absolute values are, however, somewhat too high, but keeping in mind that they were predicted based on transfer slab data the result can be regarded as a success. Due to the weak texture the final simulation of a cup test showed a very flat earing profile with a maximum close to 45° (Figure 10a,b). Compared to the experimentally measured

profiles it shows excellent agreement in terms of relative as well as absolute cup height (Figure 10b). The scatter in the measured data is due to the very flat profile (note the fine scale).

Rp_{02} [MPa]	0°	45°	90°
Exp	125	117	122
Sim	152	144	150

Table 1: Tensile flow stress of the final sheet in different in-plane directions with respect to the rolling direction. 3IVM simulation and experiment.

The major difficulty that remains to be overcome is the quantitative prediction of recrystallization nuclei of the various texture components. While the grain cluster model GIA provides already information on the deformation behavior of several texture components and, therefore, on the deformation microstructure at incipient recrystallization, there is need for a more quantitative treatment of nuclei density on a physical basis. It was exactly this deficiency that caused the over prediction of the Cube component when modeling the hot rolling process. Knowing the experimental results, yet unknown physical parameters in the present nucleation models [11] were readjusted to test if the presented TPM is capable of simulating textures accurately in any process step. The quality of the texture predictions at the different processing steps was expressed in terms of the texture index ρ [16]. As can be seen in Figure 11, the readjustment of nucleation parameters lead to a conspicuous improvement in the predicted textures, especially of the hot strip.

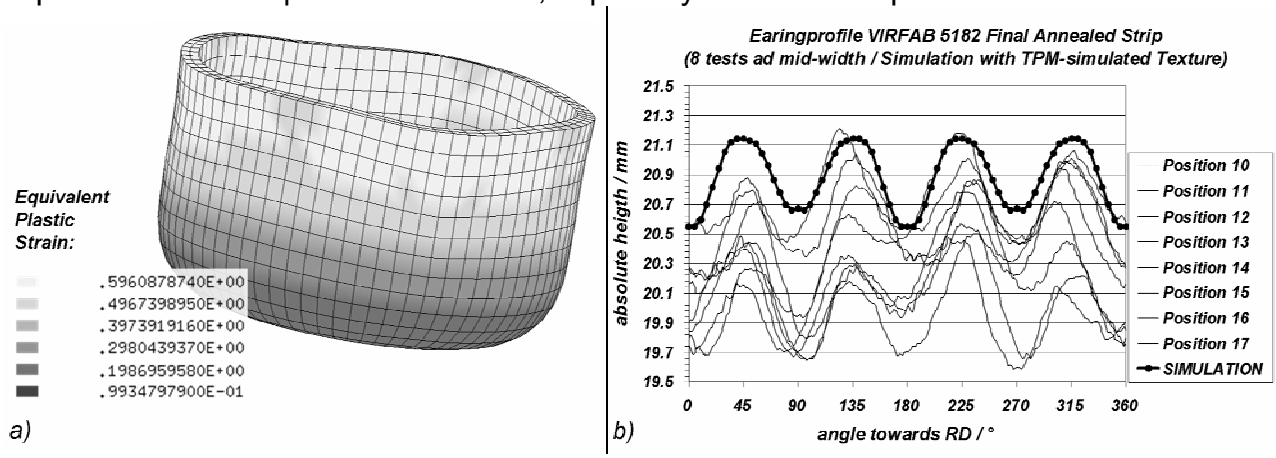

Figure 10: Simulation of a cup test of the terminal annealed sheet. (a) Distribution of equivalent plastic strain. (b) Absolute cup height over 360° with respect to the rolling direction (complete earing profile). The scatter in the measured data is due to the very flat profile (note the fine scale).

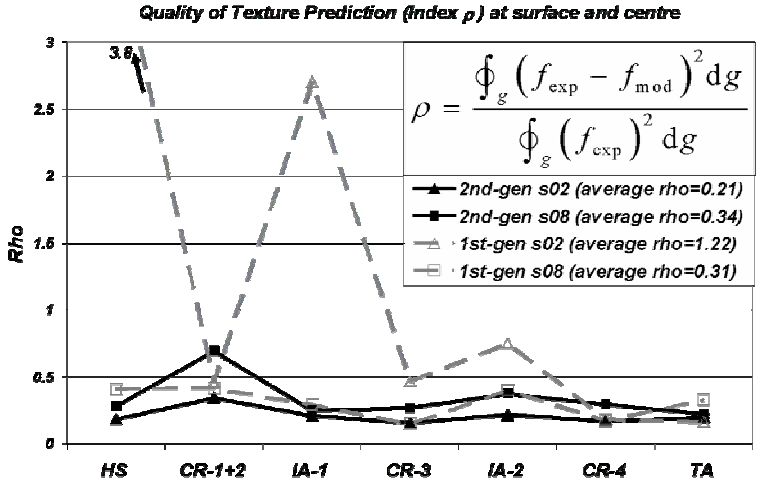

Figure 11: Improvement in the quality of the texture predictions in terms of the texture index ρ (see inserted equation) in all process steps (HS = hot strip, CR = cold rolling, IA = inter anneal, TA = terminal anneal). A value of $\rho = 0$ means exact equality of simulation and experiment. The fully predictive TPM results as described in the text are denoted as 1st generation. The so called 2nd generation results were obtained after a readjustment of the nucleation models.

6. Conclusions

A through-process modeling exercise on hot rolled, cold rolled, and annealed AA5182 was presented. The microstructural evolution was continuously simulated by physical models of work hardening, recrystallization, and rolling texture. The process in terms of temporal evolution of temperature and strain distribution was modeled by the FEM code Larstran/Shape which was interactively linked to the microstructural models to account locally for the instantaneous state and properties of the material. The TPM followed an industrial rolling schedule that allowed direct comparison of measured results with model predictions. This paper was focused on the prediction of crystallographic texture and mechanical properties. While the texture prediction at intermediate stages of the process was dissatisfactory, the prediction of the terminal texture after cold rolling and (inter-)annealing was excellent. The mechanical properties of the final sheet could be predicted satisfactorily, including a simulated earing profile obtained by a new strategy to link textures and yield locus descriptions. This can be regarded as a major step forward and it demonstrates the predictive power of physics based models. Despite these successes, the deviations at intermediate process stages revealed insufficient quantitative information on the nucleation rate of texture components, an issue in which some initial progress has been made, but which has to be addressed further during continuation of this work.

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