REVIEW PAPER

Multicrystalline Materials Analysis Based on Their Microstructure with Emphasis on Predicting Forming Limit Diagrams

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Abstract: *Phenomenological methods are more diagnostic tools than a predictor, so multi-crystalline material approaches based on their microstructures have been proposed during the last years. The purpose of this research is to review methods taking into account the effect of microstructures and texture deformation on predicting the behavior of sheet metals. These methods can be categorized into six general groups: Taylor-type models, crystal plasticity finite element methods, strain gradient methods, methods that consider dislocations, self-consistent methods, methods based on fast Fourier transform. This paper attempts to explain and compare these methods that have been used to forecasting forming limits or stress-strain curves.*

Keywords: *Polycrystalline Materials, Forming Limit, Homogenization methods, Microstructures.*

1. INTRODUCTION

Forming limit diagrams (FLDs) are good tools for predicting sheet behavior during forming processes. The FLD prediction methods are the Bifurcation method and the Marciniak-Kozinski (MK) method. The methods can be cited in another classification based on the type of geometric defect method (MK) such as Gurson–Tvergaard–Needleman (GTN) [1], structural defect, and material defect.

From the microscopic point of view, metals have crystalline structures, and it has been found that these structures directly control the mechanical properties of the metal. Microscopic structures cause macroscopic behavior, but the question is how to make the relationship between microscopic and macroscopic behavior of material that is the subject of crystal plasticity (CP). In fact, at the nanoscale, a single crystal based on its chemical composition has its atomic arrangement; this particular atomic arrangement causes the single crystal to slip in specific planes due to the applied forces. Therefore, the direction of the applied load and boundary conditions affect the deformation or in other words, the plastic behavior of the metal, i.e., the behavior of the material is anisotropic and dependent on orientation. Multi-crystal creates a so-called grain. The crystals in grain are quite close together, although there are various defects in the crystal lattice, including point, line, and plane defects. Assuming the material consists of grains, the orientation of the crystalline lattice of each grain will be different from the other grain. With advances in the field of microstructures in the micro and nano dimensions, much research has been done on using microstructural equations to more accurately predict macro-scale behavior. Studies are necessarily focused on the analysis of single crystals or multi-crystals. Approaches to transfer relationships from single crystals to multi crystals depend on materials, temperature range, and deformation process, and so on.

Several methods have been proposed, including the finite element (FE) combination with the CP which is known as CPFEM, and used in stress analysis software such as LS-DYNA, ABAQUS. This method has been so widely used as many processes have been analyzed by CPFEM so far. The CP-FEM simulations are realized by incorporating a CP simulation package (DAMASK) [2]. Multi-crystal analysis requires grid-generator interface software such as V-grain or NEPER, but the CPFE can be re-used by defining these grains and applying FE meshes. The main disadvantage of this method is its high computational cost, but it is needed to apply this approach if it is necessary to determine the stress or strain in each study point. However, there are

solutions like the fast Fourier transforms (FFT) method that directly analyzes the CP relationships, but if the objective is not to determine the stress at individual points or we want to determine strain limits, other solutions are too costly to compute. The historical evolution of such solutions for the transition from single-crystal to multi-crystal analysis began with the Sachs and Taylor method, and in the growing trend, the Taylor-relaxed model and self-constraint, the self-consistent (SC) model, the LAMEL model, the advanced LAMEL (ALAMEL) model strain gradient/interference model are noted. Of the above models, the SC model has attracted the most research because of the simplicity and accuracy of results and lower computational cost. This model is based on Eshleby's theory [3] used to solve various problems including FLDs.

For forming limit diagrams (FLDs), one can directly combine the CP relationships with the forming limit relations of the M-K method, and use either Sachs or Taylor or SC models to forecast FLDs. The effects of the material properties such as the hardening exponent of the strain rate sensitivity parameter and the shear inequality on the FLD have been investigated. If these parameters are taken into account the accuracy of the results would be better.

Reviewing researches showed that many cases need further research that has not been addressed so far. One is the effect of intra-grain effects on the prediction of the FLDs. The second problem is lacking the investigation of parameters such as strain path, normal stress effects, and extended FLDs for crystalline metals based on their microstructure.

We categorize the works that have been done yet into six major groups. Some studies are discussed on the strain gradient and its effect on forming limit diagrams. In this theory, size effects are incorporated into the modeling using strain gradient coefficients [4, 5] as a result of the material deformation, the produced dislocations, move on slip surfaces and are statistically irregular or geometrically regular in the material.

Homogenization methods are one of the important issues that have been researched in previous studies. Many methods have been suggested so far, one of them is a self-consistent method proposed by Kroner [6]. The SC model is a multi-crystalline model that considers the interaction between grains and satisfies geometric coordination and stress equilibrium conditions. In the SC model, all grains are considered as an inclusion in an extremely homogeneous effective medium (HEM). Many of the works in this field are about visco-plastic self-consistent (VPSC). Algorithm improvements numerous case studies including ideal orientations, materials with different crystalline structures such as face-centered cubic (FCC), body-centered cubic (BCC), and hexagonal close-packed (HCP), apply this method in texture evolution and validation with experimental results. In some cases, previous FC, or SC method, has been used to predict FLDs and periodic loading. Combining the M-K method and polycrystals plasticity method, the algorithm leads to a system of nonlinear equations that required the Newton-Raphson (N-R) method to solve. Answers are dependent on the initial guess and are non-convergence in some cases, these directed us to find some new extended methods in this field. One of these solutions is the improved N-R method. Studies show that grain structure is not completely regular and has some regional dislocation. Dislocations have a great effect on the plastic behavior of the materials. Recent advances have even led to steps in atomic simulation to predict the material's macro behavior. So, studies focused on intra-grain relationships in the multi-crystal plasticity approach. Some intra-grain effects, such as dislocations, have received much attention. Some have also focused on the effects of grain size on the prediction of multi-crystal plasticity. Although individual dislocation methods have been studied, describing group behavior of displacements without computer modeling is challenging. Also, computer simulations such as the discrete dislocation dynamic (DDD) method investigate the contribution of different mechanisms by eliminating other factors. The boundary value problem of dislocation dynamics is summarized, and the perspectives of growth of physical plasticity models for single crystals are discussed [7]. Larson [8] discusses the analysis procedures for derivation dislocation tensors on mesoscopic length scales. Po et al. present a review of the DDD evolution of the dislocation microstructure in persistent slip bands and the phenomenon of dislocation avalanches in micro-pillar compression [9]. Recent studies have

shown that two-and three-dimensional DDD simulations in some similar cases can predict the same results [10-12]. In more recent research, Jogi and Bhattacharyya used a fault-energy-based back-force method to explain interactions between dislocations and inhomogeneous inclusions [13]. Furthermore, Tan and his coworkers [14] proposed a novel model that has been incorporating discrete dislocation dynamics (DDD) simulations and a strain gradient plasticity (SGP) model to predict the size effect in plastic deformations of metallic micro-pillars. Both types of simulations have been used to study a range of phenomena, including plastic strain in thin sheets of Davoodi et al. [15].

Crystal plasticity fast Fourier transform (CP-FFT) method, give more valuable micromechanical information with the input from microstructure that was found by electron backscattering (EBS) [16-18]. Although CP-FEM is a very useful tool, the size and resolution of the polycrystal that can be found with this method are restricted, due to a large number of degrees of freedom that are needed by CP-FEM computations. An alternative to CP-FEM is given by the CP-FFT. The FFT formula was extended [19, 20] to compute the macro and micro response of composites, which is composed of solving the Lippmann-Schwinger equation [21] by an iterative method. The CP-FFT methods have been extended for the rigid-viscoplastic regime [22, 23], and elasto-viscoplastic (EVP) regime [24, 25] for small strains. In addition, CP-FFT methods have been extended to finite strains [26].

As we discuss many methods for complete describing we should represent so many formulas therefore, the formulation of methods did not mention in this review.

2. A REVIEW OF PREVIOUS WORKS

2.1. Taylor type models

In Taylor-based models, the complete restriction was imposed, so these models were known as fully constraint (FC). Numerous works on the plasticity of polycrystals [27-32] have used the Taylor method proposed by Asaro-Needleman [33]. Zhou and Neale [34] used the Taylor-type rate-dependent multi-crystal model. Chiba et al. [33] used the EVP multi-crystalline Taylor model extended by Kuroda and Ikawa et al. [36] and Eyckens et al. [37] utilized the Taylor rate-independent fast model introduced by Van Houtte et al.[38] Knockaert applied a Taylor multi-crystal elastic-plastic model [37, 40] Kim et al. [41] simulated polycrystals using the EVP multi-crystal model of Taylor. Pierce et al. [42] Tadano et al. [43] used a Taylor-type RVE-FEM EVP crystal model. Taylor iso-strain approaches were later modified by the general relaxation of some strain components. These changes were classified as relaxed constraints (RC). Taylor models [44-46] even RC models did not convey the stress heterogeneities that occur at the single grain level. Boundary conditions are known for a whole body, but not for individual volume elements. Taylor assumed that the plastic strain of all multi-crystal grains is equal to the microscopic plastic strain. Elastic strains are neglected. The FC model provides a solution for the distribution of stresses and strains across polycrystals, ensuring geometrical consistency is usually obtained at the grain boundaries. In real crystals, there is even a gradient of stress and strain inside the grains. However, texture-induced anisotropy is sufficiently considered by this solution for most applications. However, texture evolution is considered.

In more recent work, Gupta et al. [48] suggested a fast and robust numerical tool for the prediction of the FLDs for thin polycrystalline metal sheets using a Taylor-type crystal plasticity model. They can reduce by about 96% in terms of CPU time.

Another method is the grain interaction approach (GIA) proposed by Crumbach et al. [47]. In this approach like the LAMEL model, the cluster as a whole must satisfy Taylor's condition: the computation time is considerably longer than the other models mentioned so far [49]. Apart from the complete Taylor models, a short-range interaction (Alamel), were used for the computation of the CP model. Since all grains are assumed to have the same deformation, the interaction of grains is neglected. The Alamel model is a type of Taylor model that assumes shear strain relaxed at grain boundaries. The initial grain boundary orientation is randomly selected. The purpose of multi-crystal modeling was considered by using DDD simulations of double crystal interference in LAMEL and ALAMEL [50-52], other models [50] are based on VPSCs [54]. Furthermore, based on the generalized GIA, a relaxed grain cluster (RGC) homogenization method has been proposed [55]. From the classical CP model to advanced physics-

based CP models, dislocation-based hardening rules are embedded into the CP framework [56, 57]. The CP models exactly anticipate texture evolution in polycrystals but cannot capture size effects. In an attempt to overcome the limitations in the size effect prediction, strain-gradient CP theories have been proposed including inherent length scales [58].

2.2. CPFEM

Crystal plasticity provides a comprehensive view of the behavior of metals at mesoscale on crystalline surfaces and slip lines. Various studies have been conducted in the field of CP kinematics based on the work of Lee [59], Rice [60], Hill and Rice [61], and Asaro and Rice [62]. Then attempts were made to establish the relationship between the slip of the crystals [63] and the force, which can be attributed to Schmidt's theory that defines the CP framework in the work of Bronkhorst et al. [64] and Kalidindi et al. [65]. However, in such a structural model, there is a disregard for the presence of dislocation and absolute length scales in the reference formulation [64]. Investigation of microstructure includes random grain production, random grain orientation, and prediction of macro behavior using meso-and micro-scale information. Microstructural researches in the elastic and plastic range and the effect of grains anisotropy on stress intensity in grain boundaries, grain boundary effect, and stress-strain field have been investigated. These investigations further identify the factors affecting the mechanical behavior of different materials in the mesoscale. Ultimately, this improvement in microstructure leads to improved macro-material behavior. Therefore, intra-grain effects such as dislocations and crystallographic orientations cannot be ignored. Therefore, for accurate analysis based on physical concepts, it is obvious that the effects of dislocations on the behavior of the CP model must be taken into account.

The multilevel slip as a multilayer structure allowed the use of simplified field transformation analysis as a homogeneous framework. Numerical simulations of the relationship of both single-crystalline and multi-crystalline heterogeneous models have been reported to be more successful for 2D cases in FC improved Taylor equations, which is mostly limited to two-level slip [66]. Using two different methods: The FLD of the aluminum alloy sheet was theoretically obtained for linear paths using two different methods. For both methods, the M-K model was used to calculate FLD. The fully constraint Taylor model was used for plasticity analysis. The comparison showed that phenomenological theory could duplicate the experimental FLD on the left side of the graph but failed to do on the right domain until equilibrium elapsed. It has also shown that the CP model shows higher forming strains on the left side of the diagram and significantly lower strains on the right side of the diagram, than experimental strains. The values of M = 8, 12, or 16 for the M were selected from the yield function to investigate its effect, although M = 8 is often used for FCC material in the literature based on the Logan and Hasford recommendation [67]. The yield locations are shown by bold lines for each value of M. As the value of M increased, the curvature of the yield became less rounded in the equilibrium tensile zone and decreased in the direction of the pure shear direction. Figure 1 shows the experiments, crystal plasticity, and phenomenological method forming limit result [35].

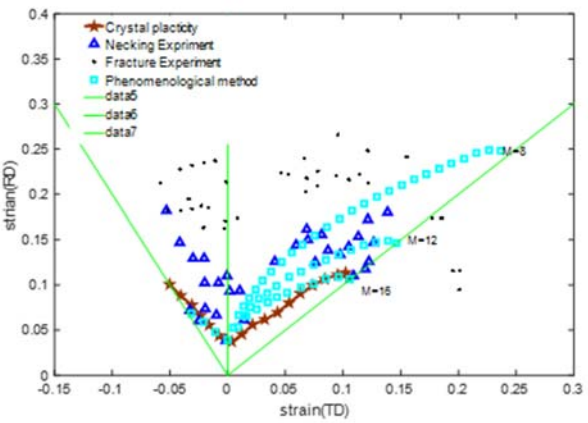

Fig. 1. Experimental and simulated FLDs for the AA1100-H24 sheet [35].

Abdolvand et al. [68] studied the stress heterogeneity in every single grain of multi-crystalline using the CPFE. For this purpose, the weighted Voronoi mosaic technique was used to construct a three-dimensional geometry of grains. The calculation of the average CPFE stress for each grain is in good agreement with the average stress measurement values. Barton et al. [69] described an approach to directly incorporate a multi-crystal plasticity model. Previously, they had to accelerate the consistent approach to

reduce the computational cost of direct embedding to achieve two or more orders of magnitude higher than classical methods. However, previous works did not permit significant evolution on crystallographic texture. For texture evolution, a discrete harmonic method is used that decomposes the integrals that represent texture effects. The basic behaviors and convergence of the new multi-crystal plasticity framework are discussed. Specific applications focus on twinning. The general framework based on the discrete harmonics approach offers a way to efficiently calculate multi-crystalline plasticity. Later studies change to other subjects and researchers try to merge CP with numerical tools such as FE for analyzing mechanical problems. Huang's valuable work on this field is very important and is the basis of many subsequent analyzes of CPFE [70]. The role of grain size and stainless steel structure was examined through the mechanical tests in digital image correlation and SEM to measure displacement and strain field and those directly supported in the mesh by grain boundaries measured by EBSD. However, there is a good agreement in the evaluation of the main slip systems between the observed experimental and computational results [71]. Panin et al. [72] showed that the surface layer and all interfaces in the solid under loading are considered as autonomous functional subsystems where the initial plastic shear begins and develops. The simulation of the plane strain tensor shows the failure plane is consistent with the basal plane. In magnesium, the failure behavior indicates that deformation mechanisms are strongly related to the material orientation and the relative activity of the deformation mechanisms. Comparison of these two FLDs revealed the lack of a measure for ductility: although these orientations had a similar strain for plane tensile failure, this was not related to plasticity under complex loading conditions [73]. The effects of ordinary texture components on the rolled aluminum alloy sheets were observed. The material response is generalized by a Taylor-type multi-crystalline model, in which each grain is characterized by its EVP relationships. In this analysis, results are obtained regarding the formation of the shear band: the critical strain at the beginning of the shear band and the shear band orientation. The developments of shear bands of the tension/compression plane strain are analyzed by the FEM. shear band developments in pure bending of plane strain are usually studied. Close regions to the surfaces in a bent sheet sample are approximately compressed or stretched in the plane strain [74].

2.3. Strain gradient methods

The strain gradient theory introduces a quantity for the length scale of material into the structural equations and it has been used to justify heterogeneous forming regions. This method removes the defect sensitivity that existed in previous phenomenological methods. Wang et al. [75] have obtained a better precision of the forming curve by using the strain gradient theory proposed by Aifantis et al. [76], to analyze the local deformation of the sheet. Using high-order strain gradients in the hardening law, they were able to uniquely justify the properties of material inside and outside the necking. They used the Hill criterion [77]. Another study by Shi and Gursen [78] investigated the effect of punch curvature on anisotropic localized necking using the Barlatt and Lian [79] anisotropic yield criterion utilizing strain gradient theory. They were able to justify the difference between the experimental forming limit curves and what had previously been achieved by other methods without using gradient methods. The material forming curves differ in terms of in-plane and out-of-plane deformation. This finding is consistent with the experimental results obtained by Hecker [80]. In other work, Zhu [81] in his doctoral dissertation discussed the effect of applying the strain gradient theory to the method of Hill and Rice and Storen [82] to obtain the forming curve. In all cases, they showed that applying the gradient theory improved the accuracy of the forming curve. Small-scale gradient plasticity, with the grain boundary model, accounted for the status of strain, slip boundary plasticity, and separation between neighbor grains. The structure of hexagonal grains in-plane strain has been investigated using finite element modeling [83].

2.4. Dislocation based methods

Beyond the defect, materials are deformed by localized plastic flow, which leads to strain softening in terms of engineering stress-strain response. Flow localization, which reveals its crystallographic defects, focuses on the activity of all dislocations. The model proposed with Barton [84] is parameterized with dislocation dynamics simulations of tensile tests and provides an

effective link between the one-nanometer defect scale and the multi-grain orientation continuous scale. Amadeo [85] identified multi-scale modeling of a specific type of pressure-dependent plasticity. It is possible to calculate the impact of pressure on both dislocation structure and collective dislocation behavior based on atomistic modeling and dislocation dynamic simulation. This study showed that CP based on FEM provides the best predictions of texture evolution in comparison with recent high-pressure experiments. Through ultra-precise measurements of the nanoscale in nickel microcrystals, direct slip phenomena are determined [86]. Franz et al. analyzed the localization of single-crystal and multi-crystal with the specific to create a link between parameters related to structure and formability. For this purpose, advanced structural modeling of single-crystalline large elastic-plastic strain, calculated for the associated micro-scale physical mechanism. The SC scheme was then used to elicit the response of multi-crystalline materials. The results of the SC model are compared with the FC model in terms of the influence of microstructural parameters on the plasticity and the predicted plasticity constraints and the corresponding strain level. Finally, it investigates the effect of strain path variations on plasticity through pre-strain analysis on FLDs [87]. Despite the experimental data for the evolution of the lattice strain of neutron diffraction measurements, a physical understanding of lattice strain and its evaluation during plastic flow is still incomplete. The SC model has focused on the kinetics of dislocation and its effect on different stages of dislocation distribution evolution in different crystallographic planes in each grain in a multi-crystalline material. This model provides a general approach in lattice strain evolution and the interpretation of internal processes [88]. Kostka et al. [89] investigated the evolution of the dislocation in the deformation of creep resistance. Luscher [90] developed a multi-physical model that extends dislocation continuity, nonlinear super-plastic effects of crystalline plasticity, internal stress, and field adaptation to simulate the single crystalline response of materials under extremely dynamic conditions. Zheng, Ballinet, and Dunne [91] evaluated the origin of plasticity-sensitive behavior overstrain rate regimes by referring to key mechanisms: mobility of dislocation and thermally activated dislocation. Zecevic et al. [92] developed a multi-crystal mean-field model based on an EPSC framework. Uniform tensile and compressive macroscopic stress-strain curves and neutron diffraction data were used to simulate and validate the model. This model predicts the anisotropic strain evolution of the hardening and texture in materials. The multi-crystal model embedded in the FEM implicit code was used. Microscopic geometry necessary dislocations (GNDs) in structural equations can be calculated by Nye's tensor. Looking at the size effects is difficult since homogenization methods consider the effect of GNDs to be the average effect of its grain length, so they have to obtain a bulk effect at the microscopic scale. In this regard, Berbenni et al. [93] investigated the intra-grain plastic slip based on the FEM. In a study by Wen et al [91], the right part of the FLD of a strain rate-sensitive FCC sheet with different compositions of two textural components and the meso-hardening effect is predicted, unlike the M-K model, no groove in the sheet was assumed. Furthermore, a rate-sensitive CP-based dislocation model is proposed to predict the FLDs without assuming an initial geometrical defect. The misorientation of the selected pairs of grains in and out of the narrow band is responsible for the initial band formation and its increase in the local necking. The analysis shows the production of FLD from multi-crystalline sheet metal of the knowledge of the grain misorientations distribution [95].

2.5. Self-consistent methods

New homogenization methods are classified into two types: (a) full-field method; (b) mean-field method. In a complete method, both long-range and short-range interactions are assumed and the micro-mechanical fields are solved on a discrete network. To overcome this problem using FEM, at the discrete grid level, the equilibrium of forces is found and the displacement compatibility is kept using the principle of virtual work [54].

In the study of Wang et al. [96, 97], the self-consistent EVP model was applied. Wen et al [94] and Lee and wen [95] used the rate-dependent CP model. Hiwatashi et al. [98] applied the plasticity model based on their previous work [99]. Savoie et al. [100] used a fully plastic rate-independent Wu et al. method [28]. Some authors like Signorelli et al. [101]

Neil and Agnew [102], Serenelli et al. [103] applied the VPSC models suggested by Lebensohn and Tome [104]. Here we describe some of the methods that have been presented so far. Initial CP methods were independent of strain rate, such CP models were used with the M–K approach to predict FLDs of different sheets with different types of primary crystallographic textures. Two separate models are used to predict FLDs. The first method involves calculating yield levels from a fully plastic rate-insensitive CP model. In the second method, the material response is based on the EVPCP model. Both methods consider texture evolution during deformation. By considering the elastic part of the deformation, the elastic-plastic model can predict the forming limit in positive strains. It has been found that the orientation of the primary texture, as well as the microstructure, has a significant effect on plasticity [102]. Knockaert et al. [37] investigated the predictive capabilities of Von Mises isotropic plasticity, Hill orthotropic plasticity and considered the forming limit by predicting local necking thinning during simulation of forming operations. Two methods have been discussed to predict the strain limit: the perturbation method and the modified maximum force criterion. In the second method, multi-crystalline plasticity is used in combination with the M–K approach. In both cases, the prediction with a thinning curve in necking is compared with the fracture forming limit curve was obtained for aluminum Signorelli et al. [101, 105] analyzed the FLD using rate-dependent plasticity, multi-crystalline VPSC method with M-K relationship. They first introduced an SC approach for FLD simulation. The model includes the effects of slip hardening, strain rate sensitivity, anisotropy, and primary texture. Finally, the FLD calculation fully predicts some experimental results that the Taylor model cannot predict for the AA6116-T4 and AA5182-O alloys.

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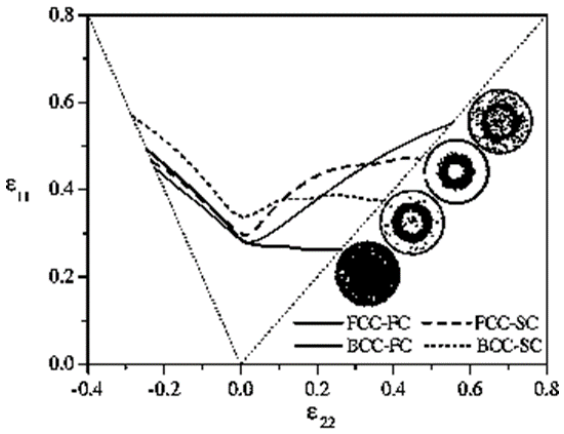
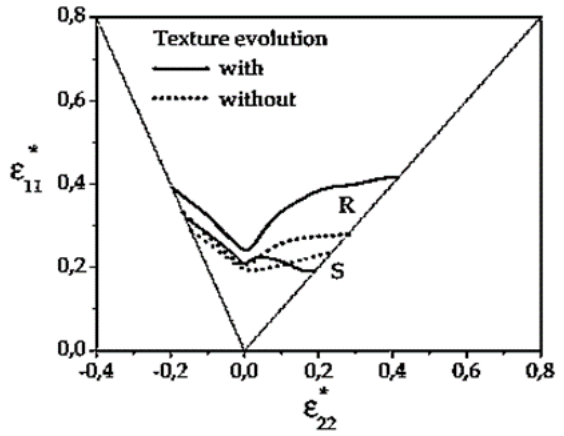
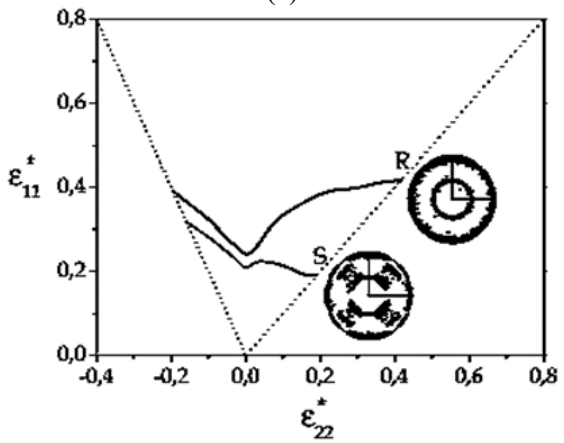


Fig. 2. Impact of the texture and interaction model on the FLD [103]



(a)



(b)

Fig. 3. a: Effect of texture evolution on the FLD, b: Effect of the initial texture on the FLD [106]

The multi-crystalline VPSC models have been applied to explain plastic deformation in materials with orthorhombic and triclinic hexagonal symmetry. The strain rate changes linearly with the stress in the HEM around the inclusion are the important assumption to solve the equation in the SC equilibrium formulation. Two cases can be identified: the tangent method and the secant method. The secant method has a tougher matrix inclusion interaction than the tangent approach and is close to the Taylor method. Besides, the interaction power of the inclusions and the matrix should not be constant but it should depend on the ability of each orientation to accommodate the particular mode of imposed deformation. Consequently, Carlos et al. [107] proposed a relative criterion for adaptation to define the variable interaction between the grain and the environment depending on their relative adaptation. A set of prediction tools consisting of a VPSC model and a machining process model was suggested. The VPSC method with sliding and twinning mechanisms in symmetric monocrystalline was used. For this model, the strain and strain rate and finally the crystallographic orientation under different machining conditions were investigated. The orthogonal shear test of aluminum alloy was performed and the texture result was predicted from the model [108]. Idiart et al. [109] used a linear comparison of the homogenization method to calculate the Hashin shtrikman boundary and the SC method. The closed-form analytical results for different symmetric cubic materials are extracted. The effect of the released changes on the boundaries is considerably larger than that previously found in quite dense polycrystals. Jiang and Weng [110] proposed an SC model to study the transfer performance of multi-crystal metals as a reduction of grain size from coarse grains to the nanometer scale.

Lebensohn et al. [111] obtained an estimation of the average intra-grain oscillation rate of the lattice rotation in multi-crystalline materials using a VPSC model. These oscillations extend the tensor measurement of the misorientation process inside every single grain. The average prediction of intra-grain oscillations of the cubic material lattice rotation rate was calculated by comparing it with the experiments. Liu and Wei [112] used the Voronoi three-dimensional granular method based on the crystalline structure and plasticity of the Staroselsky and Anand model [113]. Also, the critical shear stress is estimated at different slip/twin systems at different temperatures. Analysis of deformation at the grain surface shows that there is significant plastic stress and anisotropy between the grains [114].

Nazarov et al [115] developed the microstructure of orthogonal cutting with simple shear using a VPSC multi-crystal model. The strain incompatibility between the HEM and the grain is calculated by the results of the VPSC model in the aggregation of the disclination in the grain junctions. This disclination is then relaxed from the junctions by the slow growth of the angular displacement of the boundaries. These boundaries divide the grain into smaller volumes those orientations are incorrect and can be transformed into new grains by further deformation.

Nebozhyn et al have used a vibrational modification method to calculate the VPSC estimation for anisotropic HCP polycrystals [116]. Qiao, et al. [117] improved the behavior of large subspecies by adding thermal strain to the study of zinc-2 alloy behavior. This approach is used by introducing the thermal strain effect similar to the method developed by Turner et al. [118], by Xu et al. [119], and by Wang et al. [120]. The elasto-viscoplastic self-consistent model (EVPSC) is used. The material deformation was evaluated under different uniaxial strain paths. The material parameters for the various models are determined by fitting the experimental data from the uniaxial tensile test and compression test along the vertical direction and the uniaxial rolling tensile test. The quality of different SCs predictions is based on a comparison of microscopic deformation behavior and macroscopic mechanical response. Lattice strain and texture coefficients are predicted and the experimental results evaluated. It is revealed that the Affin and Meff = 0.1 SC models perform better than the tangent and secant models.

Yoshida [121] estimated the mechanical response of elastoplastic multi-crystals using Taylor's and Hill's incremental SC model concerning the standard and restricted Schmidt's method. Both models yielded the same result with Taylor's model while predicting the standard Schmid- SC model yields softer responses and higher strain heterogeneity than the restricted Schmid law. The results presented with the Schmidt constrained law is in agreement with previous findings for the

viscoplastic power law. Lattice strain and texture coefficients are predicted and the experimental results evaluated. It is revealed that the Affin and Meff models perform better than the tangent and secant models. Figure 4 illustrates the effect of different Affin, Meff, and secant methods on the FLD. In addition, Wang [122] studied four methods and compared them with stress-strain curves and FLDs.

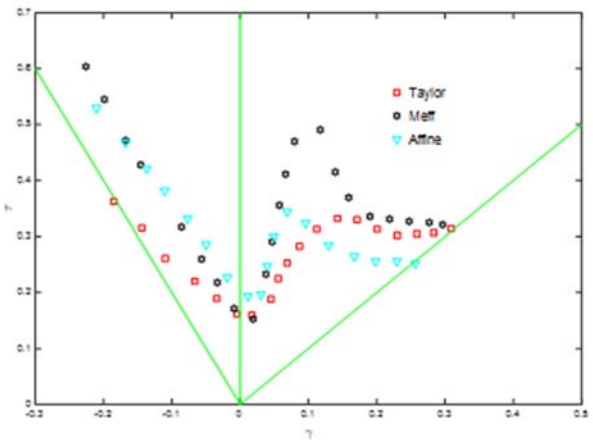


Fig. 4. Predicted FLDs for the reference sheet via different polycrystal plasticity models [122]

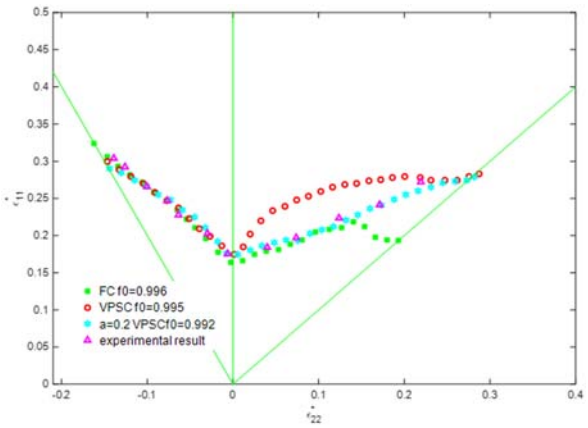
Xiao [123, 124] developed a framework for the SC model that addresses the thermo-mechanical behaviors of FCC polycrystalline metals. Neutron thermo-mechanical behavior of non-irradiated Fe alloys describes the contribution of radiation defects at the grain surface and the EVPSC behavior. Wang [125] developed the high strain EVPSC model, which includes a twin-slip deformation mechanism to study the lattice strain evolution in magnesium alloy. Wang et al. [97] evaluated different models of the SC plasticity for HCP multi-crystals by studying the deformation of magnesium alloy sheets in different uniaxial strain paths. The prediction capability of the multi-crystal model has been established based on comparison with the predicted experimental stress and R values. The full description of EVPSC can be found in a series of Wang et al. [126-130] works. The effect of crystalline orientation on FLC was investigated using three micro-macro-meso schemes with the MK analysis: MK-VPSC, MK-aVPSC, and MK-FC model. The predicted limit strain on the left part of the FLC agrees with the experimental measurements in three methods, while the differences are found under the bi-axial tension modes. In particular, the MK-VPSC predicts an unexpected limit strain profile on the right part of the FLC along the transverse direction. Only MK-aVPSC satisfactorily predicts a set of FLC measurements.

The effect of crystalline orientation on FLC was investigated using three micro-macro-meso schemes with the MK analysis: MK-VPSC tensile auto compatibility and FC model. The predicted limit strain on the left part of the FLC agrees with the experimental measurements in three directions, while the differences are found under the bi-axial tension modes. In particular, the MK-VPSC predicts an unexpected limit strain profile on the right part of the FLC for tested samples along the transverse direction. Only MK-aVPSC satisfactorily predicts a set of FLC measurements. Two predicted forming limit curves are shown in Figure 5 [131]. The defect parameter f_0 was adjusted so that the predicted limit corresponds to the experimental minimum. Limit strains are considered in plate strain conditions for samples along the RD. For the three models analyzed, MK-FC, MK-aVPSC, and MK-VPSC, the defect coefficient values are, respectively, for the hardening law are 0.996, 0.992, and 0.995, and for the saturation law, are 0.993, 0.998, and 0.997, respectively. In general, the FLD profile and the allowable limit are simulated. The strain values are reasonable for both the model interaction assumption and the hardening law description [131].

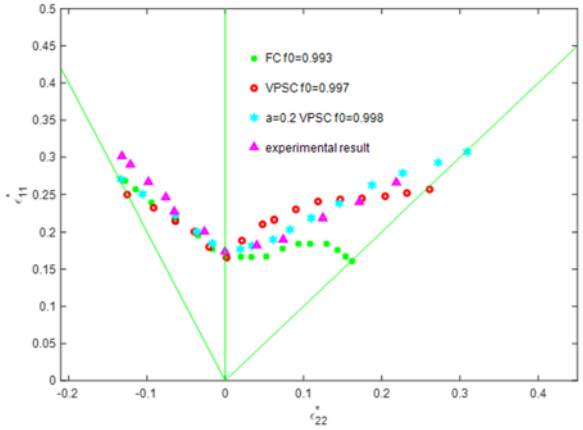
We have also studied the effect of dislocation in combination with the SC method to predict FLDs. The results have been shown in Figure 6. In this figure, we can see the result of the Taylor method, SC method, and also experimental results. This diagram has been drawn for Al. As can be seen, considering more microscopic details improved the results of the previous SC method.

In a study by Bertinetti et al. [132], the results of Wu et al. [133] were discussed. The effect of cube texture on sheet plasticity, using the MK-VPSC method was analyzed. It is shown that the simulation reached the expected results, which are the ideal cube strain with random texture calculated, over the reported results using the MK-Taylor method. Takajo et al. [134] used the VPSC polymorphic model to evaluate each grain as an ellipsoidal inclusion that is interacting with a HEM and successfully explained the mechanical response and crystal texture evolution during plastic deformation. The VPSC model is especially proper for simulating low-symmetry materials such as Mg alloys and uranium, which is a problem that cannot be solved using the traditional Taylor model. A VPSC-CP model was utilized to study the

formability of magnesium sheet alloys.



(a)



(b)

Fig. 5. Forming limit curves predicted along RD for MK-FC and MK-VPSC simulation. The triangle symbol shows experimental data a(saturation law b) hardening law [131]

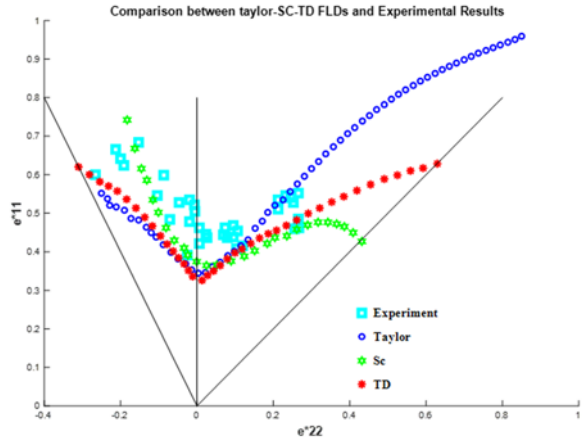


Fig. 6. Comparison of the boundary diagrams obtained by Taylor, Sernelli et al. method [141] and our new work Taylor-based dislocation method

The stress-strain curves that were found from several strain rates and the crystallographic texture measured by X-ray diffraction were used to calibrate the model. The crystallographic texture obtained from X-ray diffraction was used to calibrate the model. EBSD map of TWIP[1] deformed under tensile loads is shown in Figure 7. On the left above (a) is the inverse pole figure. The colors in EBSD are selected as the same to show the texture of the material [135].

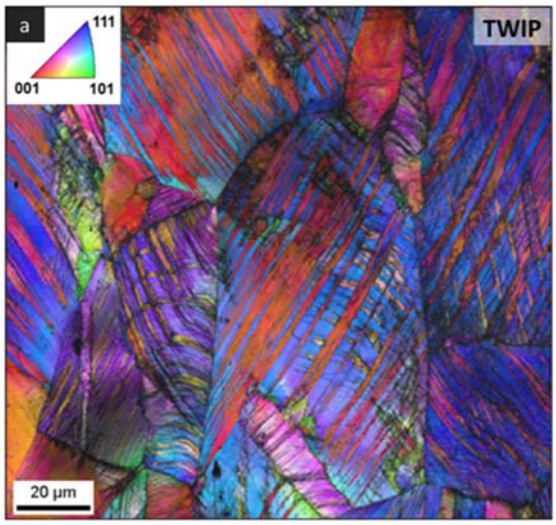


Fig. 7. EBSD map of TWIP deformed under tensile loads showing pervasive twining activities in each grain. In the left above (a) is inverse pole figure. The colors in EBSD are selected as same to show the texture of the material [135]

In Figure 8 we can also see band contrast maps at tensile strains of (a) 0%, (b) 0.14%, (c) 2.3%, (d) 7.2%, and the evolution of texture during this strain step by step. Figur10 furthermore shows change of orientation distribution function (ODF) during deformation [136]. Actually, it shows texture evolution in another way. The Orientation Distribution (OD) is a central concept in texture analysis and anisotropy. Each point in the orientation distribution represents a single specific orientation or texture component. Figures 7-9 are representatives of the texture concept for better understanding. The CP model was combined with the M-K model to find the forming limits of the magnesium

[1] Twinning-Induced Plasticity steel which is also known as TWIP steel

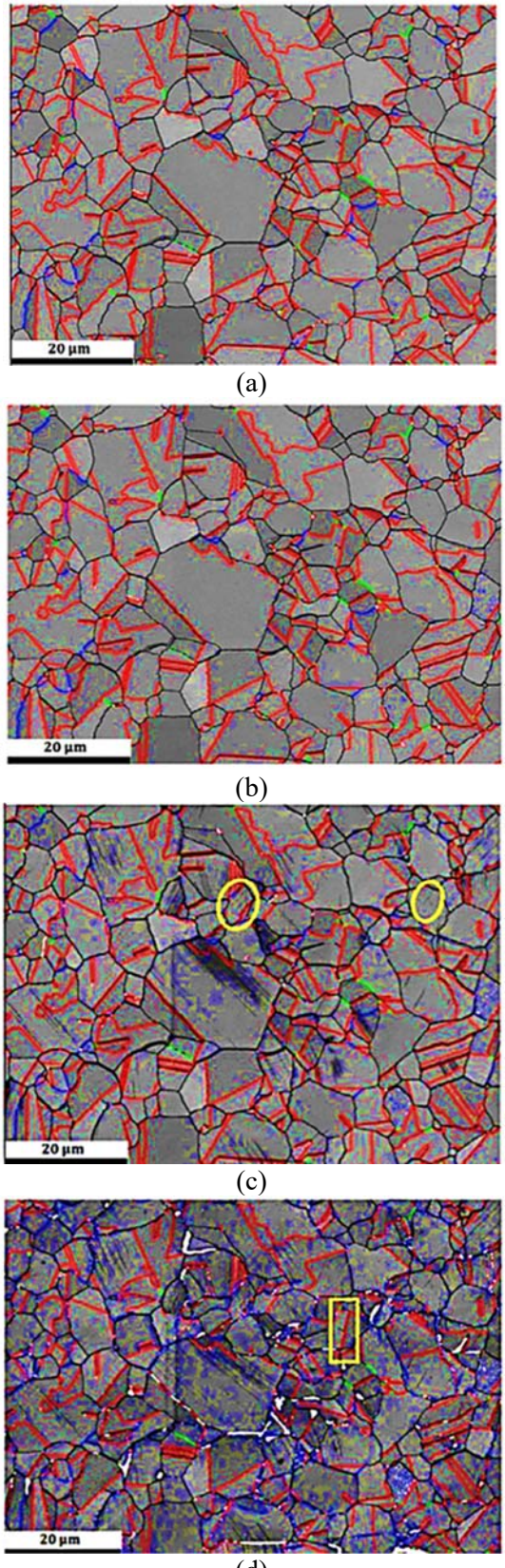


Fig. 8. Band contrast maps at tensile strains of (a) 0%, (b) 0.14%, (c) 2.3%, (d) 7.2% for Twinning-induced-plasticity (TWIP) steels [136]

sheets. These predictions are in good agreement with the experiments [137].

The VPSC and EVPSC were used to study the deformation mechanisms of magnesium alloys. However, current polycrystal plasticity models with slip and twinning involve a large number of material parameters, which may not be uniquely determined. Also, a genetic algorithm approach is developed to optimize these material parameters [138]. In another study by Schwindt et al. [139] that is supplemented by their earlier work [101], the MK-VPS model based on the N-R solution of equilibrium equations was implemented. It is a direct method to develop the strain limit calculation using the MK-VPSC model. This approach does not need the N-R method and the Jacobian matrix and only needs two calls of the usual M-K for each pre-strain increment. Further reduction in computational cost is possible by solving all the groove modes simultaneously. Therefore, for each M-K deformation step, it first examined the increase in the homogeneous region. This prevents the need for costly repetition of calculations for the homogeneous region. Wang et al. [96] analyzed the effect of the orientation of the initial defect, strain rate sensitivity, and hardening to determine MK-VPSC performance. The sensitivity of the MK-VPSC model to the grain and initial texture and texture evolution is also taken into account. It was observed that while the FLD in the strain space is sensitive to the strain direction, the stress diagram is less sensitive to the path. It has been suggested that FLSD is better than FLD in simulating the forming limit. A rate-dependent SC-CP model using the M-K model shows that the crystallographic texture has an essential influence on the FLD. For example, fiber texture had the highest level of formation in the two-axis strain path but has the lowest level of strain in the plane strain. The current model, termed "VPSC-FLD", shows that the r-value acts as a good criterion in the limiting strain [140]. Numerous researchers such as Sernelli [141] Signorelli et al. [142-144] have used the multi-crystalline model in several works, which are closer to the experimental results.

Experimental data have been used by Ramos et al. [145] for calibration and the approval of the ability of the VPSC method to predict a metal response in deep drawing and tensile processes. The rate-dependent SCCP model combined with

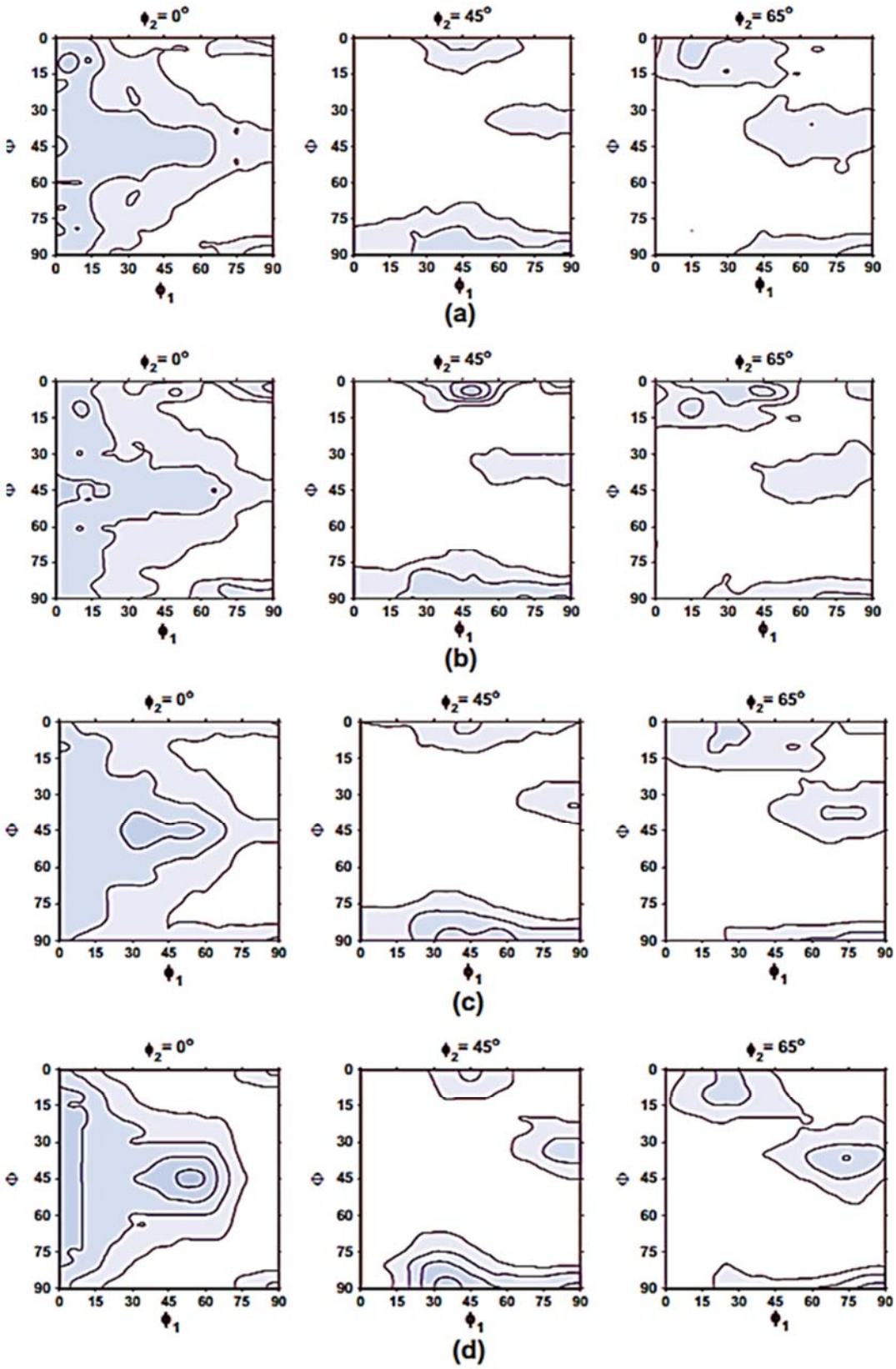


Fig. 9. φ_2 = 0, 45 and 65 ODF sections of the bulk experimental texture at tensile strains of (a) 0%, (b) 0.14%, (c) 2.3%, (d) 7.2%,[136]

the M-K model introduced by Signorelli et al. [101] compared to the MK-FC model compared to this model and has a higher computational cost. For this reason, Jeong et al. [146] decreased the computational time of the model by applying a parallel strain path in the BCC material. Different textures and γ, σ, α, η fibers were simulated. In addition, the advanced numerical algorithm previously proposed by Schwindt et al. [138] is implemented in VPSC-FLD. The new numerical algorithm improves both overall computational speed and efficiency in parallel computing. The advanced VPSC-FLD model is used for austenitic and ferritic stainless steel samples in terms of stress-strain curves, R-values, and FLDs.

The relationship between sheet plasticity and its primary texture has been shown in numerous experimental works [27, 28, 39, 135, 136, 140, 147] To understand the effect of different crystal orientations on FLD, they investigated the effect of cubic texture similar to Wu et al. [148] and Lin et al. [149], by using two interaction models: MK-FC and MK-VPSC. The comparison between the simulations with these two methods is presented and discussed. Vaitkina et al. [140] assumed that instabilities occur as a natural consequence of strain oscillations due to the absence of texture heterogeneity. Wu et al. [133] have used a similar approach and have shown that local necking is strongly dependent on its primary texture as well as its spatial orientation.

The inverse behavior at the limit strains that is reported by Wu et al. [133]; Yoshida et al. [143, 151] explain that material behavior cannot be understood solely based on the initial texture. The differences in limiting strains are related to the anisotropy of the material and its evolution along the deformation path. This increases or decreases the FLD profile. Most of the previous studies have proved that the VPSC model provides a more accurate description of the anisotropic behavior of multi-crystal materials. The generalization of multi-crystal simulations predicts higher plasticity than the Taylor type.

The EVPSC model has been developed for polycrystalline materials. At the monocrystalline level, plastic deformation mechanisms are caused by both the slip and the twin. The transition from monocrystalline plasticity to multi-crystalline plasticity is based on an SC approach. It has been shown that the difference in the predicted stress curve and EVPSC-based texture transformations and the VPSC model presented by Lebensohn and Tome [104] at large strains for a uniform load is negligible. The EVPSC predicts a smooth elastic and plastic transition for deformations related to loading and strain direction, while the VPSC model responds discontinuously due to elastic deformation. It has also been shown that the EVPSC model can capture some important empirical properties that cannot be simulated using the VPSC model [28].

A theoretical framework for the design of the SC multi-scale scheme is presented which links the overall tangent modulus of the multi-crystal velocity gradient to its nominal stress value. To predict the minimum strains of the multi-crystal, the Bifurcation and the M-K analysis, have been revised [152]. The FC and SC models based on experiments with different grain sizes were investigated. When the grain size comes near to the thickness of the sheet, the results are scattered. In different grain size conditions, comparing the experimental results with the predictions made with the different models, the GTN-Thomson models, and the MK model, are approaches that can predict failure with satisfactory accuracy [153]. The forms of strain hardening are the power law and the saturation law. The rotation of the lattice was calculated using FC and VPSC models. The correlation between orientation stability and geometrical hardening is related to the high plasticity of plane loading. The texture evolution and strain limit predicted by the VPSC are consistent with the experimental data reported by Liu and Morris [154] and Lopez [155] and how these orientations evolved in Euler space are consistent with field maps [156].

MK-VPSC method is used to calibrate the multi-crystalline model and the stress curve. Analysis of the ferrite/martensitic slip system activity shows that in the MK-VPSC framework, thinning occurs in ferrite much faster than in the martensitic phase [157]. The simulations are based on the EVPSC model and the Taylor model in combination with the MK approach. The role of the CP model and the underlying texture effect on the plasticity of magnesium alloy has been studied numerically. It has been observed that the plasticity of the materials with HCP polycrystals is very sensitive to the underlying texture density [129]. Further research can be found in references such as [158-163].

2.6. FFT based methods

The FFT algorithm converts heterogeneous spaces into Fourier space and converts the real space into mechanical spaces [23]. In contrast, field average approaches deal with complex stress heterogeneity and displacement continuity in polycrystals using the FEM method. Lebensohn et al. [111] have incorporated the numerical implementation of the multi-local non-local CP theory using the Gurtin [164]. The FFT in the non-local formula ignores the variations of the geometry in Lebensohn's EVP-FFT algorithm [23]. In recent years some works have been done [165, 166]. The FFT-based method does not use mesh, so it is a good choice for analyzing dislocation dynamic approaches. In the more recent work of Bertin and Capolungo [167], an efficient FFT-based approach for dislocation dynamics simulations in heterogeneous media has been used.

2.7. New approaches

The EVP is based on the Rate Tangent crystal plasticity Fast Fourier Transform (RTCP-FFT) conversion performed by Nagra [160]. The M-K framework [169] was used to predict the forming limit in some cubic crystals. The RTCP-FFT method, which incorporates 3D grain morphology and grain interaction, is used to calculate the FLDs of aluminum alloys. The proposed RTCP-FFT M-K model is a complete, mesh-free, efficient CP formula that can perform a comprehensive investigation of the effects of 3D microstructural properties on FLDs with very little computation cost. In addition, the FLD predicted by the M-K model based on the Taylor-type homogenization scheme (MK-TIL) has been compared. Among different microstructural properties, the grain morphology has the most influence on the predicted FLDs, and if the actual grain structure of the material is properly considered in numerical models, the predictions of FLD can be significantly improved [170].

A new homogenization method based on a combination of the Mori-Tanaka (MT) model is developed [171]. The new homogenization method is called the MT-DS model, which consists of four stages. The strain concentration tensor is calculated at each step and the homogeneous material properties are used to calculate the stiffness stress. Thus, the effects of inclusion on the stress condition of adjacent components are also considered. This strategy is repeated continuously until the equivalent hardening tensor is obtained [172].

The "second-order" homogenization method of Ponte Castañeda was used to present new SC estimates for the effective behavior of polycrystals. These two properties in combination suggest that new SC estimates derived from the second-order method may be the most accurate ever. Direct comparisons with other self-consistent estimates, including classical incremental and secant estimates, for the particular case of creep power-law, confirm these observations [173]. Berbenni et al. introduced a double-inclusion elastoplastic self-consistent (DI-EPSC) scheme for their subdomains derived from both the Eshelby and the MT properties. For twinned grains, it is shown that deformation system activities and plastic strain distributions in twins drastically depend on the interaction with parent domains. Moreover, quantitative studies on the coupled influence of secondary slip activities on the material response are proposed [174]. Spectral methods utilizing FFT algorithms address the critical question of determining local mechanical fields [175]. Djaka et al. developed an advanced crystal plasticity EVP-FFT formula combined with a phenomenological Mesoscale Field Dislocation Mechanics (MFDM) hypothesis [176].

3. DISCUSSION

This paper is concerned with the methods that consider the effect of microstructures on FLDs. Researches on this subject are very wide, so it is not possible to mention all of them. Ultimately six different types of methods were categorized. Each method has its advantages and disadvantages. As can be deduced from the above, many methods have been explored and used to predict FLDs. Computational time and accuracy of results are two important goals of any method. So merging two or more methods to use their advantages and avoid their lack is a novel idea such as FFT-CP or the work that has been suggested by Zecevic [73] that combines dislocation with the SC method using FEM code.

The history of research in this subject shows most works are about the SC method because it is usable for many cases such as low symmetry crystals. The other reason is that the SC method

considers the interaction of grains in a polycrystalline material. Due to this fact, many homogenization methods have been developed. For more information, the reference of Segardo et al. [177] must be studied. Although the SC method is widely used, it does not work in some cases as mentioned in this study. It needs more study to know why a specific method has better results in some cases and worse in others.

The simplicity and low computational cost of the Taylor model and Taylor-based methods provide a significant advantage over some methods while the weakness in precise prediction than other models, especially for some tissues can be considered as their disadvantages.

Although CPFEM and its related methods have numerous potential applications in materials simulation they have some disadvantages too. In some cases, solutions are very time-consuming.

FFT-based methods have not been used widely in previous studies. But their results are acceptable in comparison with other methods. The FFT method does not use mesh so it can be a good choice for analyzing dislocation dynamic approaches.

Strain gradient methods and dislocation-based models, consider plastic deformation at a smaller scale, so they provide more precise results. But they are difficult on the one hand and time-consuming on the other hand.

Using other homogenization methods for polycrystals that have not been used so far to study forming limit diagrams is suggested for future works also improving existing algorithms and using new algorithms will be useful.

From more recent researches we can get that the FFT method has very high potential to consider the sub-grain effects like dislocation in polycrystalline materials behavior but did not use so far for the forming limits predictions and this is a great strategy for future research.

4. CONCLUSION

- Strain incompatibility between the HEM and grain computed by the VPSC model leads to the accumulation of disclination.
- Comparing the results of the Taylor and SC approach, the SC method was more successful but has a higher computational cost than the Taylor method. This weakness was improved by solving the algorithm to reduce the N-R process.
- Taylor FC and RC models are relatively simple to run in software and do not require much computation time. Although the FC model has qualitative predictions across a wide range of material deformation processes, its predictions are slightly incorrect. For aluminum alloys, a VPSC model has also been tested. For AA I 200 it performed less accurately than the Taylor FC model. For AA5182, the results were a little better.
- It has been proven that better agreement can be achieved by using models that consider local interactions between specific grains. CPFEMs lead to much better texture predictions. However, their results are not complete either. Also, these models require enormous computational effort.
- Only advanced GIA and LAMEL models apply to a wide range of deformation modes. Their results (as shown above) are even better than those of the CPFEM model, which indicates that a much finer mesh should be used and lead to even higher computations.
- Material behavior cannot be understood solely based on the texture of the material. The differences in limiting strains are related to the anisotropy of the material and its evolution along the deformation path.
- Studies have proved that the VPSC model provides a more accurate description of the anisotropic behavior of multi-crystal materials. The VPSC reproduces material behavior, anisotropy, and evolution better. The generalization of multi-crystal simulations predicts higher plasticity of the Taylor type for the cube texture component than for the random texture in the bi-axial tension.
- The MK-VPSC model gave a good prediction of the steel behavior to accurately predict the strain limit. In

contrast, the MK-FC model predicts a very high strain at pure two-axis strain, although both MK-FC and MK-VPSC predictions appear to be accurate on the tensile side of the plane strain.

- The polycrystalline VPSC model cannot account for the effect of strain heterogeneity or orientation gradient on individual grains, which may have limitations in modeling highly inhomogeneous materials.
- The VPSC model is particularly suitable for modeling low-symmetry materials such as Mg alloys and uranium, which is a problem that cannot be solved using the traditional Taylor model.
- The SC model with grain interaction between the secant and the tangent has the best performance. Among the available self-consistent models, the Affine method leads to the best overall performance.
- EVPSC model shows better results than the VPSC model.

5. CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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