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A REVIEW ON RECENT DEVELOPMENTS OF MARCINIAK-KUCZYNSKI MODEL

A TRIBUTE TO PROFESSOR ZDZISLAW MARCINIAK

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Abstract

First, the author contributed with some aspects concerning the chronology of the developments of the Marciniak model. A review of the recent developments in the last decade of Marciniak-Kuczynski model is presented in the paper. Implementation of the new constitutive and polycrystalline models, enhancing the existing models to take into account new material, process parameters and strain-paths, modeling the Forming Limit Band concept are briefly reviewed. Capabilities of some commercial programs specially designed for the computation of forming limit curves (FLC) are also analyzed.

Key words: formability, forming limit diagrams, Marciniak-Kuczynski theory

1. INTRODUCTION

Formability describes the capability of a sheet metal to undergo plastic deformation in order to get some shape without defects. During the last decades different assessment methods of metals sheets formability have been developed. The most useful tool used to assess formability is the forming limit diagram (FLD). It has been almost 50 years since this concept was published by Keeler (1961; 1963) and then developed by Goodwin (1968) for the right side of the diagram. This method meets both manufacturer and user's requirements and is widely used in factory and research laboratories. One of the major advantages of the FLD concept is that the plastic instability can also be described by theoretical models. A detailed presentation of this method can be found in the literature (Banabic, 2000a; Banabic, 2000b; Banabic et al., 2007; Banabic, 2010; Hora & Krauer, 2006; Wagoner et al., 1989; Xu, 2006).

Various theoretical models have been developed for the calculation of forming limit curves (FLC). The first ones were proposed by Swift (1952) and Hill (1952) assuming homogeneous sheet metals (the so-called models of diffuse necking and localized necking), respectively). The Swift model has been developed later by Hora (so-called Modified Maximum Force Criterion - MMFC) (Hora &Tong, 1994; Hora et al., 1996; Hora & Tong, 2008). Marciniak (1965) proposed a model taking into account that sheet metals are non-homogeneous from both the geometrical and the microstructural point of view. Stören and Rice (1975) have been developed a model based on the bifurcation theory. Dudzinski and Molinari (1988) used the method of linear perturbations for analyzing the strain localization and computing the limit strains. Bressan and Williams (1983) have introduced so-called "Through Thickness Shear Instability Criterion" in order to take into account the shear fracture mode. Based on the analy-

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sis of the influence of the stress distribution through the thickness on the mode of failure, Stoughton (2000) has proposed a generalized failure criterion. Since the theoretical models are rather complex and need a profound knowledge of continuum mechanics and mathematics while their results are not always in agreement with experiments, some semi-empirical models have been developed in recent years. The models used for FLC prediction are presented in detail (formulation of the model, solving methods, numerical aspects, advantages and limitations) in the book (Banabic, 2010).

2. A BRIEFLY PRESENTATION OF THE MARCINIAK-KUCZYNSKI MODEL

Shortly after the publishing of the Forming Limit Diagram concept, on the basis of the experimental investigations concerning the strain localization of some specimens subjected to hydraulic bulging or punch stretching, Marciniak (1965) and Marciniak and Kuczynski (1967) developed a limit curve prediction model. This model is based on the hypothesis of the existence of imperfections in sheet metal. According to Marciniak's hypothesis, sheet metal has, from manufacturing, geometrical imperfections (thickness variation) and/or structural imperfections (inclusions, gaps). In the forming process these imperfections progressively evolve and the plastic forming of the sheet metal is almost completely localized in them, leading to the necking of the sheet metal. The realism of this hypothesis has been experimentally shown by Azrin and Backofen (1970). This model has been intensely used and developed by researchers due to the advantages it offers: it has an intuitive physical background; it correctly predicts the influence of different process or material parameters on the limit strains; the predictions are precise enough; the model can be easily coupled with Finite Element simulation software for sheet metal forming processes. The main drawbacks of this model are: the prediction results are very sensitive to the constitutive equations used, as well as to the values of the non-homogeneity parameter; in the case of advanced material models, the equation system of the model is quite difficult to solve and lacks robustness.

A few years later, Marciniak (1968) made a deep analysis of the strain localization phenomenon from the right side of the FLD and extended his initial model to cover this area. The models have periodically been brought in discussion by specialists in dedicated symposia (see Koistinen & Wang, 1978; Hecker et al., 1978; Wagoner et al., 1989; Hora & Krauer, 2006) or in special sections in conferences (NUMISHEET, NUMIFORM, IDDRG, ESAFORM etc.). Further developments of the Marciniak limit curve prediction models are synthetically described in the review paper (Banabic et al., 2010a).

On the basis of experimental investigations concerning strain localization, it was concluded that necking is usually initiated by a geometrical or structural non-homogeneity of the material (Marciniak, 1965). The analysis of the necking process has been performed assuming a geometrical non-homogeneity in the form of a thickness variation. This variation is usually due to some defects in the technological procedure used to obtain the sheet metal. The thickness variation is generally gentle. However, the theoretical model assumes a sudden variation in order to simplify the calculations (figure 1). The theoretical model proposed by Marciniak assumes that the specimen has two regions: region "*a*" having a uniform thickness t_0^a, and region "*b*" having the thickness t_0^b. The initial geometrical non-homogeneity of the specimen is described by the so-called "coefficient of geometrical non-homogeneity", *f,* expressed as the ratio of the thickness in the two regions: $f = t_0^b/t_0^a$. In the MK model, the strain and stress states in the two regions are analyzed and the principal strain ε_1^b in region "*b*" in relation with the principal strain ε_1^a in region "*a*" is monitored. When the ratio of these strains $\varepsilon_1^b/\varepsilon_1^a$ becomes too large (infinitely large in theory, but greater than 10 in practice), one may consider that the entire straining of the specimen is localized in region "*b*". The shape and position of the curve ε_1^a-ε_1^b depend on the value of the *f*-coefficient. If f=1 (geometrically homogeneous sheet), the curve becomes coincident with the first bisector. Thus this theory cannot model the strain localization for geometrically homogeneous sheets. The value of the principal strain ε_1^a in region "*a*" corresponding to non-significant straining of this region as compared to region "*b*" (the straining being localized in region "*b*") represents the limit strain ε_1^{a*}. This strain together with the second principal strain ε_2^{a*} in region "*a*" define a point belonging to the FLC. Assuming different strain ratios $\rho = d\varepsilon_2/d\varepsilon_1$, one obtains different points on the FLC. Spanning the range $0 < \rho < 1$, one gets the FLC for biaxial tension ($\varepsilon_1 > 0$, $\varepsilon_2 > 0$). In this domain, the orientation of the geometrical non-homogeneity with respect to the principal directions is assumed to be the same during the entire forming process. A detailed analysis of the Marciniak-Kuczynski model (formulation, solving methods, influence on the localization of the deformations etc.) is presented in the book (Banabic, 2010).

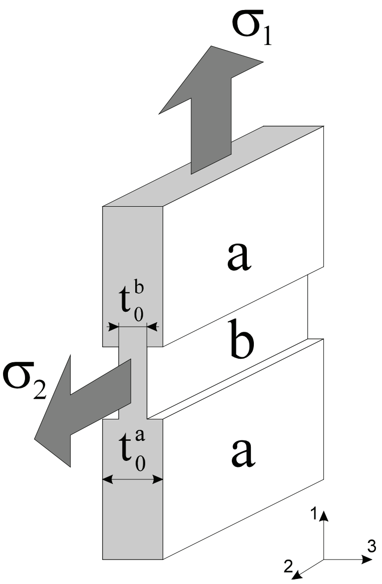

Fig. 1. Geometrical model of the Marciniak-Kuczynski theory

3. DEVELOPMENTS OF THE MARCINIAK-KUCZYNSKI MODEL

During the last decade the research in the field of the forming limits prediction using Marciniak-Kuczynski model have been focused mainly on the following aspects.

3.1. Implementation of new constitutive equations in the models used for the computation of the limit strains

The results of the FLC prediction depend crucially on the constitutive equation of the material analyzed. The effect of the shape of the yield locus on the limit strains has been analyzed in detail by Barlat and Lian (1989). As we have emphasized in Banabic et al. (2010a) and Banabic (2010), a lot of new yield criteria have been developed during the last decade. Many of those criteria have been already implemented in the computational models of the limit strains, in order to improve the predictive capabilities. Banabic have implemented various yield criteria in the MK model. For example he implemented Hill (1993) yield criterion (Banabic, 1999; Banabic & Dannenmann, 2001); BBC yield criteria (Banabic et al., 2004a; Banabic, 2004; Paraianu et al., 2006; Cazacu & Barlat, 2001; Banabic et al., 2005b; Paraianu & Banabic, 2005; Paraianu et al., 2006). In figure 2 (Banabic, 2004) is presented the theoretical FLC predicted using BBC2003 criterion (Banabic et al., 2003) versus experimental data for AA5182-0 aluminium alloy. Mattiasson and Sigvant have analyzed in a intensive program the influence of the yield locus shape on necking prediction (Mattiasson et al., 2007; Mattiasson et al., 2008; Mattiasson & Sigvant, 2008). Butuc used the Barlat et al. (1997) yield criteria (Butuc et al., 2002; Butuc et al., 2005; Butuc et al., 2006) and BBC2000 (Butuc et al., 2002). Cao and her coworkers (Cao et al., 2000; Yao & Cao, 2002) used the Karafillis and Boyce yield criterion (Karafillis & Boyce, 1993) in the MK model to analyze the effect of changing strain-paths on the FLC. Kuroda and Tvergaard (2000a) used four different yield criteria to fit a set of experimental data. Yld 2000 formulation (Barlat et al., 2003) has been included by Aretz (2004) in the MK model for studying the influence of the biaxial coefficient of plastic anisotropy on the FLCs. Kim et al. (2003) used the YLD2000 (Barlat et al., 2003) criterion to analyze the formability of a sandwich sheets. FLD for multi-layered sandwich sheets considering the material properties of each layer has been formulated with assumption of the visco-rigid plastic material based on the modified MK model (Kim et al., 2008). The anisotropic strain-rate potential was utilized for the plastic behavior of each layer. Vegter et al. (1999; 2008) have implemented their own yield criterion (Vegter & Boogaart, 2006) in the MK model. Ganjiani and Assempour (2007a; 2007b; 2008) have improved the analytical approach for determination of FLC considering the effects of

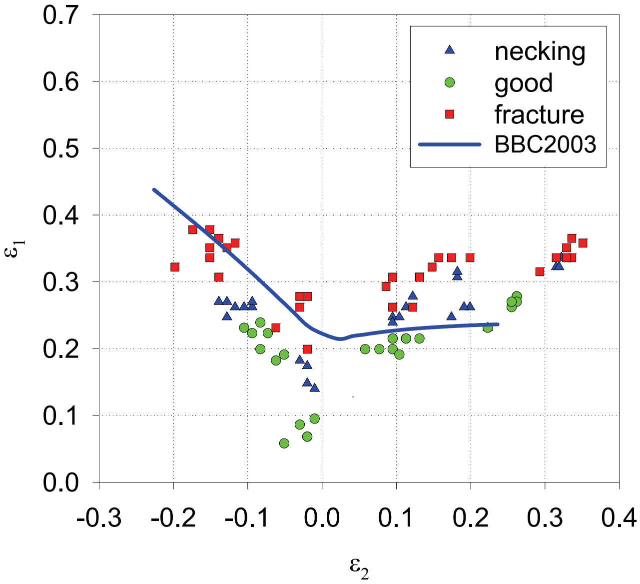

Fig. 2 Theoretical FLC versus experimental data for AA5182-0 aluminium alloy

yield functions (Hosford, 1979; Karafillis & Boyce, 1993; Banabic et al., 2003). The Teodosiu hardening model (Teodosiu & Hu, 1995) associated with different yield criteria has been implemented by Butuc et al. (2003) and Haddag et al. (2008) in the MK theory for studying the influence of the loading path change on the limit strains. The effect of BBC2003 (Banabic et al., 2003) yield surface on the prediction of FLCs and the number of experimental anisotropy parameters on the accuracy of yield functions are studied by Ahmadi et al. (2009). The polynomial yield function developed by Soare et al. (2007) has been implemented in the MK model (Soare & Banabic, 2008) and has been used to analyze the sensitivity of the MK model to the shape of the yield surface (Soare & Banabic, 2009).

The results reported by the authors listed in this section prove that the predicted limit strains are highly influenced by the quality of the constitutive models. The use of a yield criterion able to give an accurate description of the plastic anisotropy allows a better prediction of the forming limit strains. A special attention should be paid to recent criteria for modeling the anisotropic behavior of aluminum and magnesium alloys.

3.2. Implementation of the polycrystalline models

The adaptability of the texture based models to the MK theory of the strain localisation has been proved in the 1980's by Bate (1984), Asaro and Needleman (1985), Barlat and Richmond (1985), Barlat (1987) and later by Van Houtte and Toth (1993), Inal et al. (2005), Savoie et al. (1998) and Wu et al. (1997; 1998; 2004; 2005; 2007). Later on, Viatkina et al. (2001) have used such models for the computation of FLCs. The texture-based yield criterion developed by Van Houtte (1994) has been implemented in FLC models (Van Houtte, 2005), the results being compared both with those provided by phenomenological models and with experimental data (Banabic et al., 2004b). Van Houtte model (1994) coupled with a dislocation based hardening model (Teodosiu & Hu, 1995) have been implemented by Hiwatashi et al. (1998) and Van Houtte (2005) in order to predict the forming limits corresponding to change strain paths. A microstructural model developed for the description of the aluminium alloy hardening (ALFLOW) has been used by Berstad et al. (2004) to predict the forming limits of the AA3103-0 alloy. Boudeau et al. (1998), Boudeau and Gelin (2000) used the linear stability analysis combined with a polycrystalline model to predict and to analyze the influences on the FLC. A polycristal plasticity model has been used by McGinty and McDowell (2004) to conduct parametric studies of FLC. Knockaert et al. (2000) have used a rate-independent polycrystalline plasticity to predict the limit strains. The influence of the texture on the FLCs has been studied by Kuroda (2005) and Fjedbo et al. (2005). More recently, Signorelly et al. (2009), Signorelly and Bertinetti (2009), John Neil and Agnew (2009) have analyzed the forming-limit strains using a rate-dependent plasticity, polycrystal, self-consistent (VPSC) model, in conjunction with the Marciniak–Kuczynski (M–K) approach.

Coupling of the phenomenological models with the ones based on crystal-plasticity will allow better simulation of the Forming Limit Curves and the various influences (these include temperature, strain-rate, strain-path, structural evolution).

3.3. Implementation of the ductile damage models

Several types of ductile damage models have been developed during the time, e.g. Gurson, Kachanov, Chaboche, Gologanu (see details in Lemaitre, 2001). Those models have been frequently used during the last decade for the computation of the limit strains. Brunet et al. have used the Gologanu model (Gologanu et al., 1997) for calculating such limit strains (Brunet et al., 2001; 2002; 2005). The effects of texture and damage evolution on the limit strains have been studied by Hu et al. (1998). Chow et al. have developed a ductile damage model and implemented it into the MK theory both for linear (Chow et al., 1997) and complex load paths (Chow & Yang, 2001; Chow et al., 2001). An anisotropic model of Gurson type has been used by Huang et al. (2000) for the computation of the FLCs. Ragab et al. (2002) use a new model to predict the FLC for kinematically hardened voided sheet metals. Han and Kim (2003) used an original ductile fracture criterion to calculate the FLC. Lemaitre's ductile damage model has been also implemented by Teixeira (2006). Parsa et al. (2009) have determined the Forming Limit Curves for of sandwich sheet using the Gurson damage model.

Using damage models for predicting limit strain is one of the most promising directions for accurate modeling of the FLC. This aspect is due to the fact that the localization of the strains has a very good physics background. Another great advantage of these models is that it is easy to obtain the coupling between the forming process and that of the crash. Such models can retrieve crash history of the material forming process by analyzing the evolution of damage parameters in the model. One of the current limitations of the widespread application of these models is that it is very difficult to identify the damage parameters and their evolution. Currently FLC predictions using damage models have more of a qualitative than quantitative relevance.

3.4. Enhancing the existing models to take into account new material or process parameters

The influence of different parameters on the limit strains has been analyzed since the end of the 1960's. More recently, several new introduced parameters have been included in the MK and MMFC models: the shape of the yield locus (Banabic & Dannenmann, 2001), the forming temperature (Abedrabbo et al., 2006; Hora et al., 2007; Krauer et al., 2008; Zhang et al., 2008) and the coefficient of biaxial anisotropy (Aretz, 2006). The influences of the different effects on the limit strains have been studied: the effect of the surface defects (Hiroi & Nishimura, 1997) the effect of the void growth (Ragab & Saleh, 2000), the effect of grain size (Shakeri et al., 2000). Chan and Tong (2003) have developed a model of forming limits prediction for the superplastic forming. Predictive models of localized necking for strain-rate-dependent sheet metals have been developed by Mattiasson et al. (2007), Mattiasson et al. (2008), Zhang et al. (2008), Jie et al. (2009). The effect of the normal pressure on the formability of sheet metals is well known and has already been used in industry for a long time (Keeler, 1970). An analysis of sheet failure under normal pressure without assuming ductile damage has been done in the last period. Such an analysis was performed by using Swift-Hill models by Gotoh et al. (1995), Smith et al. (2003) and Matin and Smith (2005). Recently, Banabic and Soare (2008), Wu et al. (2009), Allwood and Shouler (2008) have analyzed independently the influence of the normal pressure on the Forming Limit Curve using an enhanced MK model. The experimental researches of the Single Point Incremental Forming (SPIF) (Allwood et al., 2007; Jeswiet & Young, 2005; Petek & Kuzman, 2007; Shim & Park, 2001) showed that the formability of the sheet in this process increases (the FLC is beyond the traditional FLC). Allwood et al. (2007) and Jackson and Allwood (2009) have suggested that Through Thickness Shear influences formability in SPIF process. Based on these observations, Eyckens extend the MK model to analyze the influence of the Through Thickness Shear on the FLC (Eyckens et al., 2008; Eyckens et al., 2009; Eyckens et al., 2010).

By taking into account the various material and process parameters (thickness, temperature, strain rate, pressure, thickness shear etc.) it is possible to obtain a more accurate analysis of the phenomenon of strains localization in the case of special sheet metal forming processes (high-speed sheet forming, superplastic forming, hydrostatic deep-drawing, incremental sheet forming, etc.). It is also possible to obtain a better prediction of the limit strains for these special sheet forming processes.

3.5. Extending the FLC models for non-linear strain-paths

During the sheet metal forming processes, the material is usually subjected to complex strain patterns. Nakazima et al. (1971) has proved that complex loads modify the shape and position of the FLC's. This fact imposes the determination of the limit strains for complex strain-paths. The development of the computational models for complex strain-paths in the frame of the MK theory has become an active research field in the early 1980's (see Barata & Jalinier, 1984; Barata et al., 1985; Wagoner et al., 1989). The refinement of those models has been intensively approached only during the last period. Butuc et al. (2002a; 2002b; 2005; 2006) has developed a general computer code for the FLC computation in the case of complex load paths using various hardening models (both phenomenological – Swift, Voce, and miocrostructural ones – Teodosiu-Hu). Rajarajan et al. (2005) have validated the CRACH model for the case of complex strain-paths. Cao et al. (2000), Yao and Cao (2002) analyzed the influence of the changing strain paths on the limit strains. Hiwatashi et al. (1998) have used Teodosiu's model for studying the influence on the strain-path change on FLCs. Kuroda and Tvergaard (2000b) have studied the effect of the strain-path change on the limit strains using four anisotropic models.

In real sheet metal forming processes the material is subjected to complex strain-paths. Therefore, the prediction of the FLC for the case of changed strain-path is crucial for a correct prediction of the limit strains in the industrial applications.

3.6. Using advanced numerical methods for the solution of the limit strain models

Wagoner and his co-workers have used the finite element method for the numerical determination of the limit strains in the frame of the MK theory (Narashimhan & Wagoner, 1991; Zhou & Wagoner, 1991). The simulations reproduce the standard M-K model. The influence of the mechanical parameters (strain hardening, normal anisotropy, strain-rate sensitivity) on the FLD_0 has been analyzed. The authors proposed that the FLD_0 be used as fitting parameters between predicted and experimental results. Later on, an internal state variable plasticity/damage model was employed in explicit and implicit FE codes to predict the FLC by Horstemayer et al. (1994). Tai and Lee (1996), predict the FLC by using FEM based on a coupled elasto-plasticity coupled damage constitutive law. Narashimhan and Nandedkar (1996), Nandedkar and Narashimhan (1999), analyzed the influence of changing the strain paths and work hardening on the FLC using FE modeling. Gänser et al. (2000) proposed a micromechanical approach method to predict the FLC. A 3D model has been used to study the instability of a two-phase material. Due to the limitation of the rather simple model the results are more qualitative than quantitative. An algorithm with incremental load to solve the MK model was implemented in FE code by Evangelista et al. (2002). Van den Boogaard and Huetink (2003) made a comparison between the MK analysis and a FE analysis with membrane and shell elements. A biaxially loaded grove plate is simulated with a FE model. The benefit of the FE model (boundary conditions, non-proportional loading, friction with the tools) are presented. Lademo et al. (2004) made a FEM-based calculation and the results of the simulation are compared with analytical calculations based on the MK-theory. The authors found a fair agreement between the FEM-based and analytical FLD-calculations. Lademo et al. (2005) implemented a coupled model of elasto-plasticity and ductile damage in LS-DYNA for plane-stress analysis. The results show that shell element analysis is applicable to predict the important failure mechanism of plastic instability of the sheet metal. Berstad et al. (2004) analyzed the localized necking phenomenon in non-linear FE simulations. The FLC for an aluminium alloy has been predicted based upon FE simulation of a patch of shell elements with a random Gauss-distributed thickness. Brunet et al. (2005) implemented a non-local model (modified damage Gologanu's model and coalescence Thomason's model) in a FE dynamic-explicit code. The results show that the strong mesh dependence caused by strain softening is avoided by the damage and coalescence model, respectively. Paraianu and Banabic (2005) implemented the BBC 2003 and Cazacu-Barlat yield criteria in ABAQUS finite element code to predict the FLC. The analysis proves the capability of the finite element method to predict the strain localization. Teixeira et al. (2006) used a Lemaitre's ductile damage model coupled with Hill's (1948) yield criterion within the framework of Continuum Damage Mechanics (CDM) to calculate the FLC. The results reported shows that the model was able to capture the damage evolution and predict the location of possible material failure. Hopperstad et al. (2006) analyzed the influence of serrated yielding and PLC effect on the predicted forming limit curve.

The results reported by the researchers previously mentioned indicate that the finite element method for the prediction of the forming limit curve is, at least quantitatively, useful, efficient and applicable.

3.7. Modeling the Forming Limit Band concept

In industrial applications, the variability of the parameters of the raw material (mechanical characteristics, thickness, surface quality, etc.) is a source of uncertainty in relation with the position of the FLD. The first results on the influence of the variability of the material parameters on the Forming Limit Curves have been reported by van Minh et al. (1973). Karthik et al. (2002) have studied the coil-to-coil, test-to-test and laboratoty-to-laboratory variability of sheet formability using OSU formability test. On the basis of the variability of the limit strains established by experiments (Carleer & Sigvant, 2006; Rechberger & Till, 2004), Janssens et al. (2001) introduced the Forming Limit Band concept. This is a strip containing almost all of the limit strain states. The concept has been extended by Strano and Colosimo (2006a; 2006b). Asuming the variability of the mechanical parameters of the sheet metal, Banabic and Vos (2007), Vos and Banabic (2007) have developed a computational method of the Forming Limit Band. In the figure 3 is presented the predicted the Forming Limit Band versus experimental data for DC-01 grade (0.7 mm thickness) (Banabic et al., 2010b).

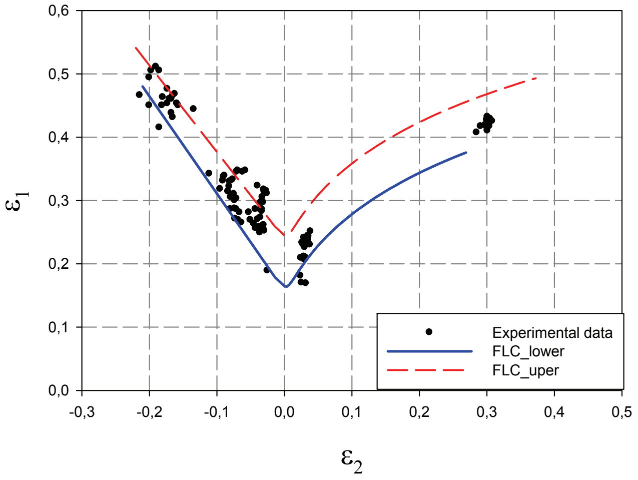

Fig. 3. Predicted Forming Limit Band versus experimental data for DC01 grade

A new model based on the assumption of the thickness variations of the sheet (modeled by use of random fields) to predict the Forming Limit Band has been proposed by Fyllingen et al. (2009). An approach to statistically evaluate the forming limit in hydroforming processes when taking into account the variations in the material parameters has been reported recently by Kim et al. (2009).

The deterministic models assume that all the input parameters are well-defined constant values corresponding to the arithmetic average of the experimental data (i.e. the deterministic approach does not take into account the dispersion of the parameters). An important source of the errors in the FLC prediction is the deterministic approach. The experiments show two aspects. First of all, the mechanical parameters of the metallic materials have a pronounced variation during the forming processes. The second aspect experimentally proved is the dispersion of the instantaneous values. In order to improve the performances of the simulation programs, it is necessary to take into consideration both the variability and the dispersion of the input data by using statistical methods. The Forming Limit Band (FLB) as a region covering the entire dispersion of the forming limit curves tries to improve the so-called "robustness" of the technological design process.

3.8. Developing commercial codes for FLC computation

In the last decade, more commercial programs for the limit strains prediction have been developed. In this section the most significant ones are presented.

Based on a Marciniak-Kuczynski mode, Banabic (2006), Jurco and Banabic (2005) have developed so-called FORM-CERT commercial code. The BBC 2005 yield criterion (Banabic et al., 2005a) is implemented in this model. This yield criterion can be reduced to simpler formulations (Hill, 1948; 1979; Barlat, 1989). In this way, the yield criterion can be also used in the situations when only 2, 4, 5, 6, or 7 mechanical constants are available. The numerical results can be compared with experimental data, using the import/export facilities included in the program. The FORM-CERT code can be directly coupled with the finite element codes.

Using the CRACH algorithm (based on the Marciniak-Kuczynski model), Gese and Dell (2006) have developed two software: CrachLAB, a product for prediction of the initial FLC and CrachFEM a product for coupling with the FEM codes. Criteria for ductile and shear fracture have been included in CrachFEM to cover the whole variety of fracture modes for sheet materials. The material model used to calculate instability describes: the initial anisotropy (using Hill (1948) and Dell et al. (2008) models), the combined isotropic-kinematic hardening and the strain rate sensitivity Dell et al. (2008). CrachFEM is now included in the FEM codes Pam-Stamp and PamCrash of ESI Group.

4. CONCLUSIONS

In the past, the FLC models provided an approximate description of the experimental results. Such models were used especially for obtaining qualitative information concerning the necking/tearing phenomena.

At present, the FLC models allow a sufficiently accurate prediction of the limit strains, but each model suffers from its own limitations. There is no model that can be applied to any sort of sheet metal, any type of crystallographic structure, any strain-path or any variation range of the process parameters (strain rate, temperature, pressure, etc.).

The future research will be focused on a more profound analysis of the phenomena accompanying the necking and fracture of the sheet metals. On the basis of the analysis, more realistic models will be developed in order to obtain better predictions of the limit strains. New models will be developed for prediction of the limit strains for special sheet metal forming processes: superplastic forming, forming at very high pressure, incremental forming etc. Commercial codes allowing the quick and accurate calculation of the FLC's both for linear and complex strain-paths will be developed. The texture models will be also implemented in such commercial programs. The FLC computation will be included in the finite element codes used for the simulation of the sheet metal forming processes. The aim is to develop automatic decision tools (based on artificial intelligence methods) useful in the technological design departments. The stochastic modeling of the FLC's will be developed in order to increase the robustness of the sheet metal forming simulation programs. More refined, accurate and objective experimental methods for the experimental determination of the limit strains (e.g. methods based on thermal or acoustic effects) will be also developed.

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Streszczenie

W pierwszej części pracy przedstawione są chronologicznie ostatnie osiągnięcia w zastosowaniach modelu Marciniak-Kuczynski. Następnie zaprezentowany jest przegląd prac z tej tematyki opublikowanych w ostatniej dekadzie. Omówiono nowe prawa konstytutywne i modele polikryształów wzbogacające istniejące modele poprzez uwzględnienie nowych materiałów i parametrów procesu, zmian drogi odkształcenia, a także poprzez wprowadzenie koncepcji pasma odkształceń granicznych (ang. Forming Limit Band - FLB). W pracy przedstawiono również ocenę możliwości różnych programów specjalnie dedykowanych do wyznaczania krzywych odkształcalności granicznej (ang. forming limit curves - FLC).

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