Sādhanā Vol. xx, No.x, xx xxxx, pp.xx–x
DOI 12.3456/s78910-011-012-3

Review on Different Hardening Models for Computation of Deep Drawing Process Simulation

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Abstract. we address herein various hardening models and their suitability in computational modelling of deep drawing process wherein magnesium alloy AZ31 as blank material. insight on all basic and advanced hardening models. The basic models as well as advanced models were illustrated in usefulness of them in metal forming. It is purely depends on the researcher to select the appropriate hardening model for extracting the real computational behavior resembling the true hardening property.

MS received xxxx; revised xxxx; accepted xxxx

Keywords. Strain hardening, Isotropic hardening, kinematic hardening, mixed hardening, deep drawing.

1 Introduction

In practice, different metal forming processes such as deep drawing, stamping, or bending operations are required in manufacture of automotive parts, beverage or food cans, panels of aerospace etc. In the last few decades the design of sheet metal manufacturing processes such as deep drawing had been significantly influenced by modern tools, e.g. the large field of numerical simulations that were based on FEM. The yield behaviour of material is essentially known and transformation of it into material model is significant during the numerical simulation. Hardening behavior is one such an important material parameter to be considered in numerical modeling of the forming process for simulation. The car body components for example becomes more complex in geometry point of view and leading to a mixture of different stress conditions during forming like deep drawing, stretching and shearing. As a consequence of these reasons the material models pertaining to hardening had become important. The inferior formability and/or larger spring-back are also technical obstacles to overcome. Spring-back is a critical factor in the quality of final products, making the designing of forming tools more difficult and expensive. Since the sheet spring-back is the elastic unloading response after complex, large-strain deformation paths such as those encountered in sheet metal forming operations [1], its accurate simulation requires a proper constitutive description incorporating complex behavior such as Bauchinger effect, transient behavior, permanent softening etc. The Computational models considering all these effects can strive to replace the expensive and time consuming trial and error methods in study of forming behavior that were used so far in conventional design. Through understanding of different models to be used for inducing the hardening behavior in constitutive equations is of complex task in computational simulation of deep drawing and other processes had successfully implemented in the last couple of decades. The finite Element Methods (FEM) is quite successful to simulate metal forming processes, but accuracy of the drawn parts depends upon the constitutive laws and their parameters identification. The development of material models and their use in computational plasticity is of much importance in reducing the cost and time.[2,3]

Metals loaded beyond the yield point deform plastically and it is often essential to predict the behavior of plastic deformation that necessitates formulations to be used in computational models for evaluation and assessment of sheet metal deformation behavior. The different hardening models that were used for computer simulation are described in the next section for proper understanding the deformation behavior.

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2 DIFFERENT TYPES OF HARDENING MODELS

There are various models that were developed for evaluation of the influence of strain hardening and other factors influencing of deformation. The different types of models studied in this paper are as follows.

1. Perfectly elastic model
2. Ideal rigid plastic material model
3. Elastic- perfectly plastic model
4. Hardening material models under monotonic loading
   (a) Rigid linear hardening model
   (b) Elastic linear hardening model
   (c) Ludwig power law
5. Hardening models under cyclic loading
   (a) Isotropic hardening model
   (b) Kinematic hardening model and
   (c) Mixed hardening model.

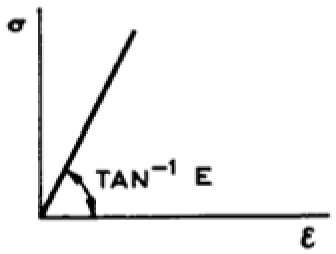

Figure 1. Perfectly elastic model

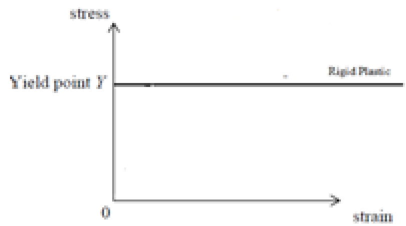

Figure 2. Rigidly Plastic material model

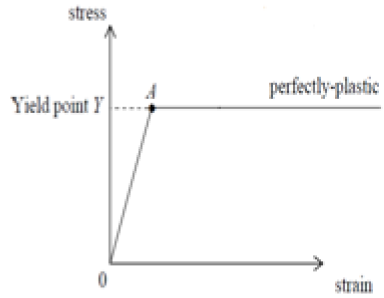

Figure 3. Elastic – perfectly plastic material model

2.1 *Perfectly elastic model*

A basic engineering notion is that material behavior in the first stage of deformation is approximately elastic. i.e., the material returns to its initial stage after the external cause (force) is removed. The perfectly elastic material which significantly obeys Hooks law is as shown in fig. and follows the law

$$\sigma = E\epsilon. \tag{1}$$

Brittle materials like glass ,ceramics and some other cast irons can be modeled with this model. For that have short rupture elongation(upto 2%) and goes to ruptrue immediately after yield point perfectly elastic model is used. This model is is only suitable where the deoframation is within the elastic deforamation and is not suitable for sheet metal forming in which plastic deformation is the main essentiality in bringing permanent deofrmation.

2.2 *Rigid Plastic Model*

The deformation should at least partially permanent. For metals, this pattern of permanent deformation is known as plasticity. A rigidly plastic material does not have any elastic nature of deformation and it is rigid up to yield point. Once the applied stress reaches the yield limit, the material subjected to 100% plastic deformation and this deformation continuous further without any increment of the stress applied. The rigid plastic material model is as shown in the Fig. 2. In this rigidly plastic material model the specimen exhibits no deformation until the applied stress reaches the critical value i.e., the yield point. As soon as the applied stress in the specimen reaches the yield limit the deformation takes place uninterruptedly as long as the applied stress is maintained at yield stress(Y). if the stress lessened due to unloading the deformation seizes.

2.3 *Elastic-Perfectly Plastic Material model*

An elastic – perfectly plastic material model is one which takes into account the elastic nature of the material and does not account for strain hardening of the material. While using this model, the stress increment is linear until the yield point, and beyond the yield point the material offers no resistance to deformation as well as no strain hardening of the material and hence uninterrupted deformation takes place as long as the stress applied is maintained at yield point. Perfectly elasto–plastic material can yield a constant stress state that exhibits no hardening and essentially the yield surface remains constant.

2.4 *Hardening models under cyclic loading*

As a material yields, hardening defines the change of yield surface with plastic straining. Experiments show that if you plastically deform a solid, then unload it, and then try to reload it so as to induce further plastic flow, its resistance to plastic flow will have increased. This is known as strain hardening. The clear understanding of stress-strain behavior of metals under a cyclic loading is very essential for computational modeling of materials. There are many different models that have been developed for the case of cyclic plasticity. Material models developed for correct description of cyclic plasticity is complicated due to cyclic hardening or softening effect. Some materials show very strong cyclic softening (ex. Copper) or cyclic hardening (ex. Stainless steels) and others less pronounced steels(medium carbon steels). A ductile material subjected to stresses beyond the elastic limit will essentially yield for larger plastic deformations. The phenomenon of hardening models is very essential to describe the computational deformation behavior of the material. Indeed, the appropriate hardening model is necessarily being selected for accurate description of the flow stress as well as the yielding behavior of the material. In essence, the hardening phenomenon occurs due to micro level behavioral changes during dislocation slip between crystallographic planes. Flow stress increases with increasing plastic deformation and it is manifested due to hardening tendency of the material. In

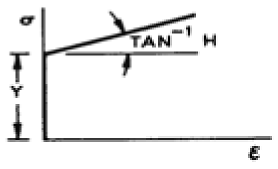

Figure 4. Rigid linear work hardening model

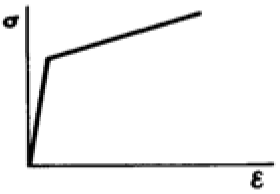

Figure 5. Elastic linear work hardening model

general, the hardening behavior can be classified into two basic types that deal with translation and expansion of the yield surface. Distortional hardening is yet another type of hardening behavior based on which the shape of the yield surface evolves during plastic deformation. The very important hardening models that were used are 1) isotropic hardening 2) kinematic hardening and 3) mixed hardening models.

2.5 *RIGID LINEAR WORK HARDENING MODELS*

In the below figure true stress-true strain diagram of a rigid linear work hardening material is given. In such a material deformation is not observed until tensile stress reaches to yield point. When tensile stress reaches to yield point plastic deformation starts and in order to increase deformation stress should be increased also. In this model stress varies linearly with plastic strain (linear work hardening). As in rigid perfectly plastic model elastic deformation is neglected in this model. This model is applied to plastic bending analysis of beams.

2.6 *Elastic linear work hardening model*

This model shows elastic linear hardening behavior.

2.7 *Ludwig Power Law*

Some empirical equations that fit to the experimentally obtained true stress-true strain curves have been developed.

One of them is developed by Ludwig and valid in constant temperature and strain rate situations;

$$\sigma = Y + H\overline{\epsilon}^{n} \tag{2}$$

where

Y: Yield strength

H: Material dependent strength coefficient

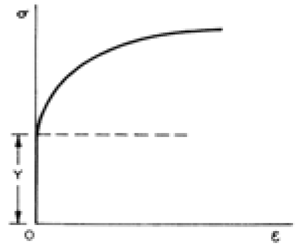

Figure 6. Ludwig power law

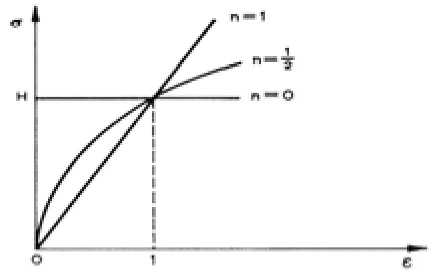

Figure 7. Different forms of Ludwig law (for Y = 0)

n: Work hardening power.

For different work hardening power values different stress-strain curves can be generated as shown in Fig.

2.8 *Swift power law*

The work hardening law recommended by Swift dipicted by the following relation

$$\overline{\sigma} = A(B + \epsilon)^{n} \tag{3}$$

Where

B: Prestrain coefficient

n: Work hardening power i.e., a measure of work hardening

A: is a function of direction of stress.

In the operations where the large deformations take place the Swift law yields results closer to the real deformation process. However, the Swift law is more complex than other models.

Isotropic hardening

It is evident that the easiest way to model the strain hardening behavior is to consider the yield surface to increase in size but its shape remains constant while plastic deformation. This method is easy to implement in numerical simulation code and has been widely used in describing the work hardening behavior of sheet metal in stamping process like deep drawing. However, the drawback with this method is that it over predicts the yield stress in reverse loading. At any point

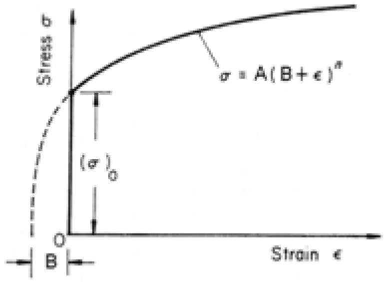

Figure 8. : Swift curve

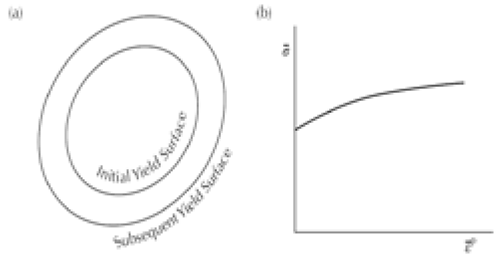

Figure 9. (a) isotropic hardening (b) Schematic equivalent stress-strain curve

considered on the surface of the material loaded for deformation can be subjected to any one among the three conditions may occur i.e., unloading, neutral loading, and loading. The stress state under unloading can move back to original surface to the elastic domain. In this condition, plasticity will not occur. If neutral loading occurs, the state of stress will move on the yield surface, causing no plasticity to occur. A material plastically deformed under applied load can be reversed by reversed load. Upon reloading after reversed load manifests for higher (increased) yield stress in comparison to initial loading and it's elastic deformation limit will increase in the subsequent loading. This increase is of same nature for both tension and compression and can be termed as isotropic hardening.

In other wards isotropic hardening is a type of hardening when the initial yield surface expands uniformly in all directions in stress space during plastic deformation as shown in the Fig below. Basically, isotropic hardening means that a material loaded in tension past yield, when it is unloaded and then subjected to compression, it will not yield in compression until it reaches the level past yield that reached when loading it in tension. In other words if the yield stress in tension increases due to hardening the compression yield stress grows the same amount even though you might not have been loading the specimen in compression. Isotropic hardening states that the yield surface expands uniformly during plastic flow. Isotropic hardening is often used for large strain or proportional loading simulations. In essence the isotropic

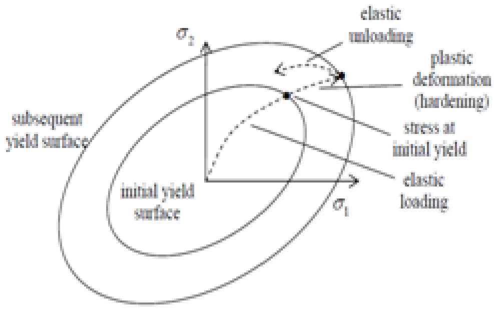

Figure 10. Evolution of yield surface under Isotropic hardening in biaxial stress space

hardening is where the yield surface remains the same shape but expands with increasing stress as shown in above Fig 99.

In isotropic hardening, the yield function can be defined as:

$$f\sigma_{ij} = Y^2 \tag{4}$$

where Y denotes the yield stress of the material. Y also represents the radius of the yield locus. As the magnitude of Y increases, the yield locus expands in all directions. Y can be expressed as a function of strain hardening quantities such as the plastic work per unit volume or the equivalent incremental plastic strain.

The yield function can also be expressed by taking hardening factor K into account as

$$f(\sigma_{ij}, K_i) = f_o(\sigma_{ij}) - -K = 0 \tag{5}$$

According to Swift, the general law can be as follows.

$$\sigma_f = C(\epsilon + \epsilon_o)^n \tag{6}$$

where σ_f is flow stress, ϵ is the plastic strain, ϵ_0 is the elastic strain and n is strength coefficient The yield surface according to Von Mises yield criteria, the initial yield the yield surface can be defined as

$$f_0(\sigma_{ij}) = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} - Y \tag{7}$$

where Y is the yield stress in uni-axial tension.

In biaxial testing any combination of stress inside the initial yield surface, inner ellipse in the Fig 10 is in the elastic region. Once the part is taken beyond the initial yield surface, the part experiences plastic deformation. With isotropic hardening, the center of the yield surface remains fixed but the size of the surface increases. Any stress state inside the new yield surface (outer ellipse in Fig 10) will experience elastic deformation and new plastic deformation occurs when the stress state reaches outer ellipse.

Isotropic hardening model is an appropriate model for the effective simulation of monotonous processes in which the load direction does not change. The different types of isotropic hardening laws suitable for elasto plastic material are as depicted in the table 1. Among the above isotropic hardening functions the Voce and Swift laws have been widely used as hardening definitions for sheet metals. The Voce hardening law is widely used for steels which generally exhibit a saturating hardening behavior in a sense that the rate of increase of stress decreases with additional plastic deformation and turns into zero at very high plastic strains. On the other hand, the Swift hardening law is preferred for most aluminum alloys that exhibit a non-saturating hardening behavior. A combined Swift-Voce (CSV) law incorporates both saturating and non-saturating hardening functions through the use of a weighting factor. This results for a superior fit for both steels as well as aluminum alloys. It is to be noted that appropriate selection of isotropic hardening function gives appropriate fit for monotonic loading conditions such as unaxial tensile test conditions for all orientations of the test sample with respect to the rolling direction. But many metal forming processes involve reversed loading (e.g. imposed by draw beads in deep drawing) or other non-proportional loading conditions (e.g. imposed by a sequence of stamping processes). In case of using an isotropic hardening function for such load reversal conditions, the hardening in reversed loading is overestimated resulting in an exaggeration of the predicted springback and residual stresses. Using a kinematic hardening function might be an alternative. This is discussed in the following section. But the Bauschinger effect can be observed in cyclic loading is the reason for not using of isotropic hardening models for cyclic loading.

Table 1. Different Isotropic hardening models

S.No	Hardening Equation	Name of the Law
1	$\sigma^{iso}= \sigma_o$ +K ϵ^{p^n}	Ludwig (1909)
2	$\sigma^{iso}=$ K ϵ^{p^n}	Hollomon (1944)
3	$\sigma^{iso} = \sigma_o + Q(1 - e^{-b\bar{\epsilon}^p})$	Ludwig (1909)

Nomenclature

σ_y Yield stress
B_1 Alphabet b
Y Yield strength
n Strength hardening exponent

3 Conclusion

Various hardening models were described in this article and it is essential to select suitable hardening model during the simulation of sheet metal operations

Acknowledgement

I thank the Principal and the management of Sreyas Institute of Engineering and Technology for the research support in bringing this paper.

References

[1] Myoung-Gyu Lee, Daeyong Kim, Chongmin Kim, M.L. Wenner, R.H. Wagoner and Kwansoo Chung (2007), A practical two-surface plasticity model and its application to spring-back prediction, International Journal of Plasticity 23, 1189–1212

[2] Klaus-Jurgen, Bathe, Francisco Javier Montans , On modeling mixed hardening in computational plasticity, Computers and Structures 82 (2004) 535–539.

[3] D. Rakic, M. Zivkovic, R. Slavkovic, M. Kojic, Stress Integration for the Drucker-Prager Material Model Without Hardening Using the Incremental Plasticity Theory. Journal of the Serbian Society for Computational Mechanics / Vol. 2 / No. 1, 2008 / pp. 80-89

[4] A.H. Mahmoudi, S.M. Pezeshki-Najafabadi, H. Badnava, Parameter determination of Chaboche kinematic hardening model using a multi objective Genetic Algorithm, Computational Materials Science, 50 (2011) 1114–1122.

[5] Kwansoo Chung, Taejoon Park, Consistency condition of isotropic–kinematic hardening of anisotropic yield functions with full isotropic hardening under monotonously proportional loading, International Journal of Plasticity 45 (2013) 61–84.

[6] ACS Reddy, S Rajesham, PR Reddy, TP Kumar, J Goverdhan, An experimental study on effect of process parameters in deep drawing using Taguchi technique International Journal of Engineering, Science and Technology 7 (1), 21-32 , 2015

[7] ACS Reddy, S Rajesham, PR Reddy, J Ramulu, A Kumar Experimental study on strain variation and thickness distribution in deep drawing of axisymmetric components, International Journal of Current Engineering and Technology 2014

[8] ACS Reddy, S Rajesham, PR Reddy, Experimental and simulation study on the warm deep drawing of AZ31 alloy, Advances in Production Engineering & Management 10 (3), 153 2015

[9] ACS Reddy, S Rajesham, PR Reddy Evaluation of limiting drawing ratio (LDR) in deep drawing by rapid determination method, Internal Journal of Current Engineering and Technology 4 (2), 757-762 2014

[10] SR A C Sekhara Reddy Determination of LDR in deep drawing using reduced number of blanks, ICAMM-2016 Materials Today 5 (5 (2018)), 27136–27141 2018

[11] SRTM A. C. Sekhara Reddy, Experimental and Simulation Study in Deep Drawing of Circular Cups for Determination of LDR, International Conference on Emerging Trends in Engineering (ICETE) Emerging 2020

[12] TPK Reddy A C S, Forming Limit Diagram for Sheet Metal Forming: Review, International Journal of Advance Research and Innovative Ideas in Education 2017

[13] ACSR Srinivas Reddy, Thummala, B. Nageshwar Rao, Parametric Optimization of Warm Deep Drawing Process Aluminium Alloy 1100, International Journal of Engineering Development and Research 5 (Issue 4), 6 2017

[14] AM BABU, DR VVRLSGangadhar, ACS REDDY Modeling and Analysis of Tube Axial Flow Fan by Comparison of Material Used and Changing the Number of Blades, 2014, International Journal of Scientific Engineering and Technology Research 3, 2014

[15] Michel Goossens, Frank Mittelbach, and Alexander Samarin. *The LaTeX Companion*. Addison-Wesley, Reading, Massachusetts, 1993.