Journal of Engineering and Development, Vol. 18, No.2, March 2014, ISSN 1813- 7822

Factor Affecting The Determination Of Wrinkling Limit Diagram For Metal Sheets

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Abstract :

Wrinkling is one of defects in sheet metal forming operations, it is produced by a compressive stress field. The prediction of wrinkling is important for the design of stamping and deep-drawing processes . Wrinkling is unacceptable in the outer skin panels where the final part appearance is crucial. Wrinkling on the mating surfaces can adversely affect the part assembly and part functions, such as sealing and welding. In addition, severe wrinkles may damage or even destroy dies. Therefore, the prediction and prevention of wrinkling are extremely important in sheet metal forming.

In this paper the wrinkling limit diagrams for steel , aluminum and aluminum alloy (AA3103 , AA5182) sheets have been determined theoretically using Marciniak-Kuczynski analysis with Hosford anisotropic yield function .

The effect of strain hardening exponent, normal anisotropic ratio, Strain rate sensitivity exponent and imperfection factors could be determined theoretically, it is shown that the highest wrinkling limit curve appeared in steel sheet and the lowest curve in aluminum alloy (AA 3103)sheet (low resistance of wrinkling). The increase in each of the value of factors (strain hardening exponent, normal anisotropic ratio, Strain rate sensitivity exponent and imperfection factor) improve the resistance sheet against wrinkling.

Keywords : Wrinkling limit diagram(WLD), anisotropic yield criterion, MK analysis.

العوامل المؤثرة لتعيين مخطط حد التجعد للصفائح المعدنية

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الخلاصة :

يعتبر التجعد احد العيوب في عمليات تشكيل الصفائح المعدنية، تتكون نتيجة إجهاد انضغاطي. من المهم ان نتنبأ بظهور التجعد عند تصميم في عمليات الكبس والسحب العميق. التجعد غير مقبول في أطراف الصفيحة الخارجية. التجعد في اطراف الصفائح يؤثر على تجميع الأجزاء ووظائفها، بالإضافة الى أن التجعد الحاد يسبب الى ضرر او تدمير قالب التشكيل. إذن التنبؤ بالتجعد ومنعه ضروري في عمليات تشكيل الصفائح.

في هذه الدراسة تم تعيين مخطط حد التجعد للصفائح الصلب والالمنيوم وسبائك الالمنيوم(AA3103 , AA5182) نظريا باستخدام تحليل (M.K) مع نظرية الخضوع (Hosford) .

تم تعيين نظريا تأثير كل من معامل الاصلاد الانفعالي ومعامل تباين الخواص ومعامل حساسية معدل الانفعال ومعامل عدم التجانس. وقد تبين أن أعلى منحني لحد التجعد ظهر في صفيحة الصلب وأدنى منحني في صفيحة سبيكة الألمنيوم (AA3103) اقل مقاومة للتجعد. وعند زيادة قيم كل من العوامل(معامل الاصلاد الانفعالي ومعامل تباين الخواص ومعامل حساسية معدل الانفعال ومعامل عدم التجانس) ادى الى تحسين مقاومة الصفيحة ضد التجعد.

Notation

Symbol	Definition	Unit
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses	MPa
$\varepsilon_1\ \varepsilon_2\ \varepsilon_3$	Principal strains	
m	Strain rate sensitivity	
n	Strain hardening exponent	
σ'	effective stress	MPa
$\acute{\varepsilon}$	effective strain	
$\dot{\varepsilon}$	strain rate	1/sec
$\dot{\varepsilon}'$	effective strain rate	1/sec
ρ	ratio of minor strain to major strain	
ta	thickness of the sheet	
tb	Thickness of groove	
α	Principle stress ratio	
f	Imperfection factor	
e	Yield criterion index	
K	Strength coefficient	MPa
R′	Normal plastic anisotropic ratio	
φ	ratio of principal stress to effective stress	
β	Ratio of effective strain to principal strain	
M-K	Marciniak-Kuczynski analysis	
F1a	Principal Force in region (a) in M.K analysis	N
F1b	Principal Force in region (b) in M.K analysis	N
WLC	Wrinkling limit curve	

1. Introduction:

Production engineers and researchers have paid much attention to the behavior of wrinkling in sheet metal forming operation over the last decade. It is difficult to define criteria for describing the stability in metal forming. In general, wrinkling may be affected by various factors including material property, punch and die geometry, blank geometry and holding conditions, interface friction and lubrication state. Numerous studies have been carried out on the relationship between wrinkling and material characteristics[1-3].

One of the most representative works was performed by Yoshida[4] and was generally directed towards investigation of the conditions under which wrinkling would occur in a large shallow pressing, characterised by the well known Yoshida buckling test. Karima and Sowerby [5] have attempted a bifurcation approach to the study of wrinkling during deep drawing. They treated flange wrinkling during deep drawing without a blank holder as a problem of elastic–plastic buckling of an annular plate. Their results indicate that a high rate of hardening has favorable effect on the prevention of buckling when deep drawing through conical and tapered dies. However, Narayanasamy and Sowerby [6] has showed that the stainless steel 304 sheets which have a low value of normal anisotropy and a high value of normalized hardening rate, have better resistance to the formation of wrinkles. The wrinkling behavior of cold rolled and annealed sheet metals with the aim of prediction the onset of wrinkling during drawing through tractrix and conical dies, has been studied in addition [7]. Di and Thomson[8] have used the neural network principle for the prediction of strain at the onset of wrinkling based on the Yoshida material parameters.

The effect of geometrical variables that affect the onset of wrinkling during deep drawing has been investigated by Wang et al. [9], using a neural network approach. Kim and Son [10] studied wrinkling behavior of sheet metals using a numerical analysis for evaluating a wrinkling limit diagram (WLD) for an anisotropic sheet subjected to biaxial plane stress.

Optical measurements of wrinkles on thin polymer films might provide a simple and accurate alternative to more traditional techniques used to determine thicknesses, mechanical properties (Stafford, Harrison, Beers, Karim, Amis, Vanlandingham, Kim, Volksen, Miller and Simonyi [11]), and residual stresses (Chung, Chastek, Fasolka, Ro and Stafford[12]). Similarly, measuring wrinkles on cell membranes might provide important insight regarding cell locomotion (Burton and Taylor [13], Harris, Wild and Stopak [14]). Applications that exploit wrinkling to tune the optical properties of cavities (Kolaric, Vandeparre, Desprez, Vallee and Damman [15]) and to shape capillaries for micro-fluidic purposes (Ohzono, Monobe, Shiokawa, Fujiwara and Shimizu [16]) also seem relevant.

The purpose of this paper is to determine the limit of wrinkling for all sheets(steel ,aluminum and aluminum alloy (AA3103 , AA5182)) by using wrinkling limit curve theoretically and compare. And determine the effect of strain hardening exponent, normal anisotropic ratio, Strain rate sensitivity exponent and imperfection factors in wrinkling limit curve.

2. Chemical composition and Mechanical properties:

The chemical composition of the aluminum, mild steel, aluminum alloy for AA5182 and AA3103 sheets were shown in **Table (1,2,3 and 4)** .

Table(1) Chemical analysis of Aluminum

Material	Ti%	Mg%	Si%	Mn%	Cu%	Fe%	Zn%	Cr%	Al%
Aluminum	0.017	0.015	0.1	0.02	0.2	0.21	0.03	0.004	**Rem.**

Table(2) Chemical analysis of Mild steel

Material	C%	P%	Mn%	S%	Si%	Mo%	Cr%	Cu%	Fe %
Mild steel	0.2	0.003	0.2	0.02	0.05	0.005	0.04	0.02	**Rem.**

Table(3) Chemical analysis of AA5182 sheet

Material	Mg%	Mn%	Fe%	Si%	Cu%	Cr%	Ti%	Al%
AA 5182	4.51	0.34	0.18	0.08	0.05	0.02	0.02	**Rem.**

Table(4) Chemical analysis of AA3103 sheet

Material	Mn%	Fe%	Mg%	Si%	Cu%	Zn%	Ti%	Al%
AA 3103	1.16	0.46	0.009	0.07	0.004	0.003	0.006	**Rem.**

The mechanical properties of all sheets were obtained from tensile test. The values of Strain Hardening exponent (n), Strain rate sensivity (m), Yield stress 0.2% offset (YS) and Strength coefficient (K),which were used in the theoretical determination of WLD, are shown in **Table (5).**

Table (5)Mechanical properties of sheets

Material	Strain Hardening exponent (n)	Strain rate sensivity (m)	Strength coefficient (K)[MPa]	0.2% Proof stress [MPa]
Aluminum	0.21	0.001	280	82
Mild steel	0.27	0.018	940	410
AA3103 Sheet	0.226	0.002	180	55
AA5182 Sheet	0.3232	0.0001	585.2	143.5

The plastic anisotropic ratio (R) were obtained from tensile test with different specimen angle(0º,45º,90º) and after determined Normal plastic anisotropic ratio (R´) by using eq.(2.1). which were used in the theoretical determination of WLD, are shown in **Table (6).**

$$R' = \frac{R_0 + 2R_{45} + R_{90}}{4} \qquad (2.1)$$

Table(6) plastic Anisotropic ratio and normal plastic Anisotropic ratio

Material	Normal plastic Anisotropic ratio (R´)
Aluminum	0.83
Mild Steel	1.51
AA3103	0.5675
AA5182	0.8872

3. Theoretical Analysis:

The theoretical wrinkling limit diagrams presented in this work were calculated using a more general code(M-K analysis and Theory of plasticity) for predicting the wrinkling limits under linear strain paths. The code consists of a main part and several subroutines allowing the implementation of hardening law, yield function.

The geometry of neck formation and the element of sheet undergoing plastic deformation are shown in **Figure.(1)**. Following the M-K analysis , based on a simplified model with assumed pre-existing thickness imperfection in the form of a groove perpendicular to the principal stress directions, The sheet is composed of the nominal area and weak groove area, which are denoted by `a' and `b', respectively. The initial imperfection factor of the groove, ƒ0, is defined as the thickness ratio (ƒ0=t0b/t0a); where (t)denotes the thickness and subscript (0) denotes the initial state. A biaxial stress state is imposed on the nominal area and causes the development of strain increments in both the nominal (a) and the weak area (b).

The yield criterion proposed by Hosford[17] was used in the calculation in the plane stress state , this criterion is obtained as follows :

$$(s')^e = \frac{1}{(R'+1)}\left[(s_1)^e + (s_2)^e + R'(s_1 - s_2)^e\right] \ldots\ldots (3.1)$$

using e = 8
from eq.(3.1)

$$j = \frac{s_1}{s'} = \left[\frac{(R'+1)}{1+(a)^e + R'(1-a)^e} \right]^{\left(\frac{1}{e}\right)} \quad \text{.........}(3.2)$$

The behavior of material can be represented in the form of Power law

$$s' = Ke'^{n} \dot{e}'^{m} \quad \text{.........}(3.3)$$

The ratio of the principal stress and strain are defined as follows:

$$a = \frac{s_2}{s_1} \qquad , r = \frac{e_2}{e_1} = \frac{de_2}{de_1} \quad \text{.........}(3.4)$$

The associated flow rule is expressed by

$$de_{ij} = dl \frac{\partial s'}{\partial s_{ij}} \quad \text{.........}(3.5)$$

and

$$de_1 = \frac{de' j^{e-1}}{(R'+1)} \left[1 + R'(1-a)^{e-1} \right] \quad \text{.........}(3.6)$$

$$de_2 = \frac{de' j^{e-1}}{(R'+1)} \left[(a)^{e-1} - R'(1-a)^{e-1} \right] \quad \text{.........}(3.7)$$

using condition of constant volume in plastic deformation

$$de_1 + de_2 + de_3 = 0 \quad \text{.........}(3.8)$$

from eq.(3.8)

$$de_3 = -\frac{de' j^{e-1}}{(R'+1)} \left[1 + (a)^{e-1} \right] \quad \text{.........}(3.9)$$

then, by applying the principle of equivalence of plastic work

$$s' de' = s_1 de_1 + s_2 de_2 \quad \text{.........}(3.10)$$

the compatibility condition is given by

$$de_{2a} = de_{2b} \qquad (3.11)$$

from Marciniak-Kuczynski analysis[18].

$$f = \frac{t_b}{t_a} \qquad (3.12)$$

$$f = f_o \exp\left(e_{3b} - e_{3a}\right) \qquad (3.13)$$

the equilibrium condition requires that the applied load remains constant along the specimen

$$F_{1a} = F_{1b} \qquad (3.14)$$

from eq.(3.3 - 3.14)

$$j_a\left(e'_a + de'_a\right)^n \dot{e}'^m_a = f j_b\left(e'_b + de'_b\right)^n \dot{e}'^m_b \qquad (3.15)$$

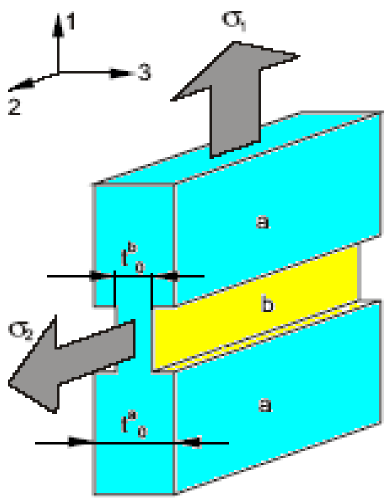

Fig .(1) Marciniak-Kuczynski analysis

Equilibrium equation (3.15), is an equation that can be found and solved numerically. Imposing a loading path (ρa), a finite increment of strain is also imposed in region (a), and numerical computation is performed by using computer program (Fortran power Station) to determine the limit strain of a strain path in the WLD , and the limit strain is determined when [(dεb1/dεa1)> 10] in the range of strain ratios from (-2 to -0.5)[19].

4. Results and Discussion :

The method of solve equations is numerically by using finite increment of strain in multiple step of computer program **Fortran power station 4** to determine the limit strain of a strain path(-2 to -0.5), the input of program is mechanical property of sheet (strain hardening exponent , strain rate sensivity, imperfection factor and normal plastic Anisotropic ratio),and out put of program are major strain and minor strain .

Figure(2) shows the theoretical wrinkling limit diagram of Steel sheet using Hosford yield criterion .

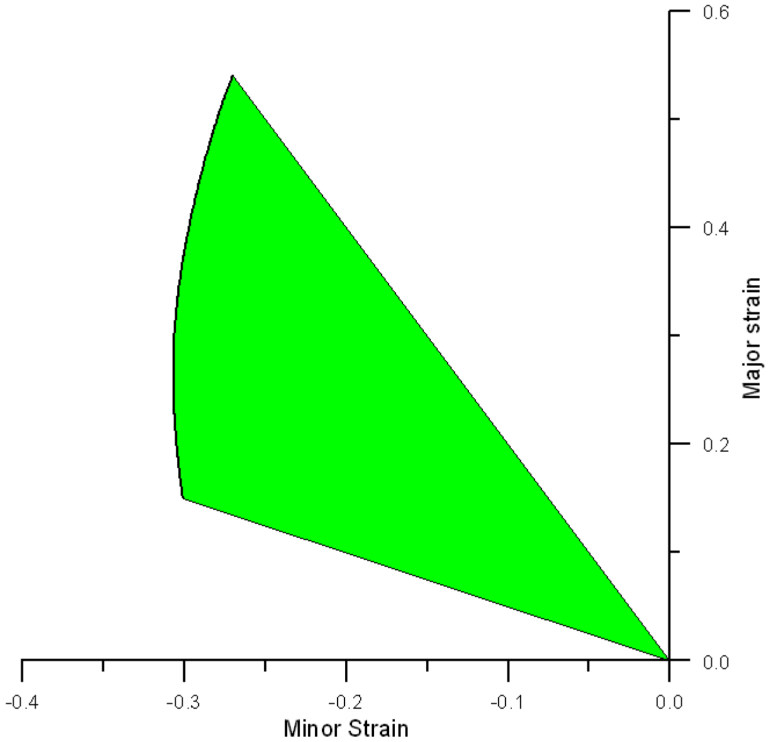

Fig .(2) Wrinkling limit diagram of Steel sheet

Figure(3)shows the theoretical wrinkling limit diagram of Aluminum sheet using Hosford yield criterion .

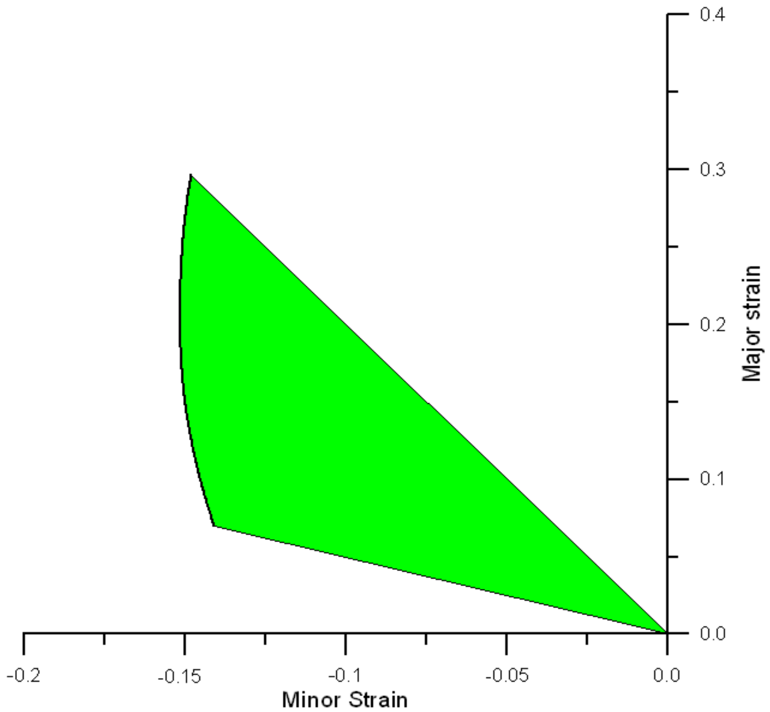

Fig .(3) Wrinkling limit diagram of Aluminum sheet

Figure(4)shows the theoretical wrinkling limit diagram of Aluminum alloy **AA3103** sheet using Hosford yield criterion .

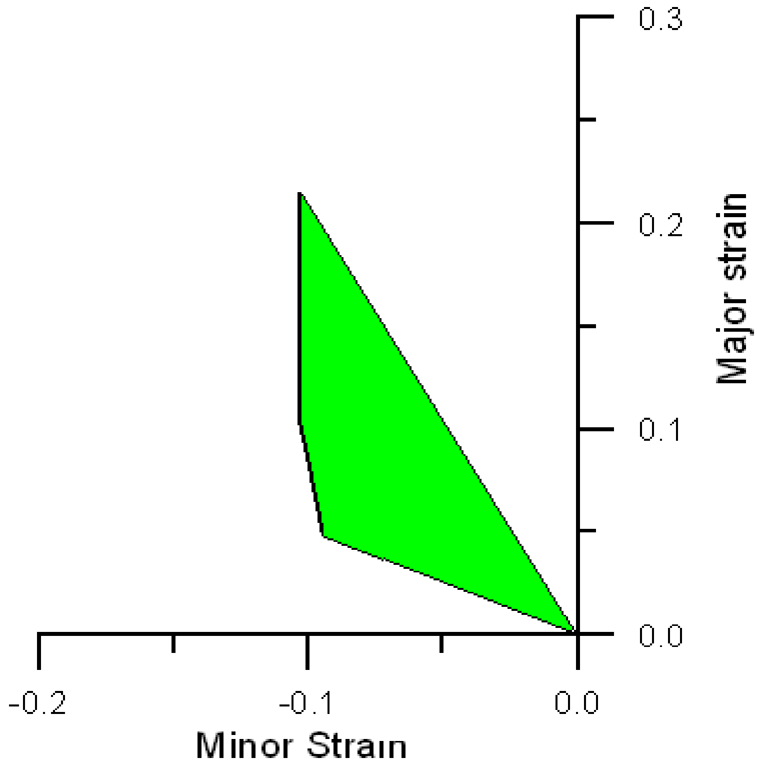

Fig .(4) Wrinkling limit diagram of Aluminum alloy AA3103 sheet

Figure(5)shows the theoretical wrinkling limit diagram of Aluminum alloy **AA5182** sheet using Hosford yield criterion .

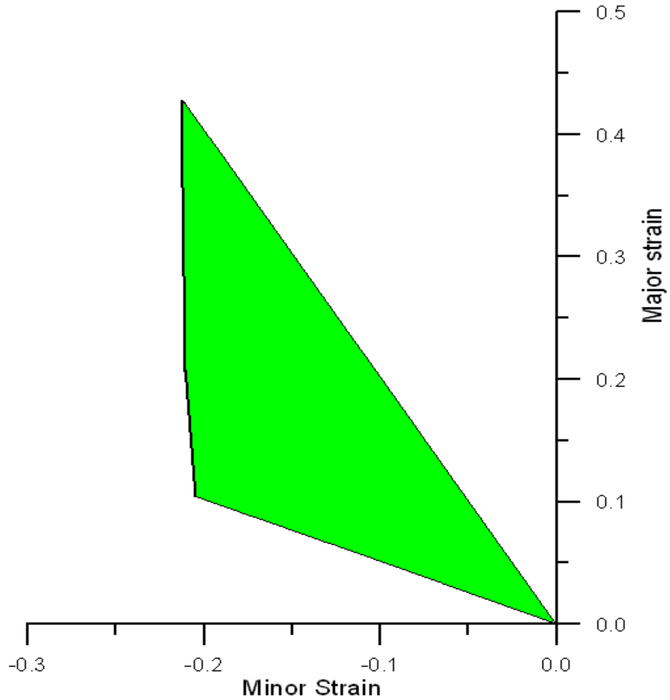

Fig .(5) Wrinkling limit diagram of Aluminum alloy AA5182 sheet

Figure(6)shows the effect of strain hardening exponent (n value) on the wrinkling limit diagram. It can be seen the limits of wrinkling limit curve increase while increase the strain hardening exponent(n value) .

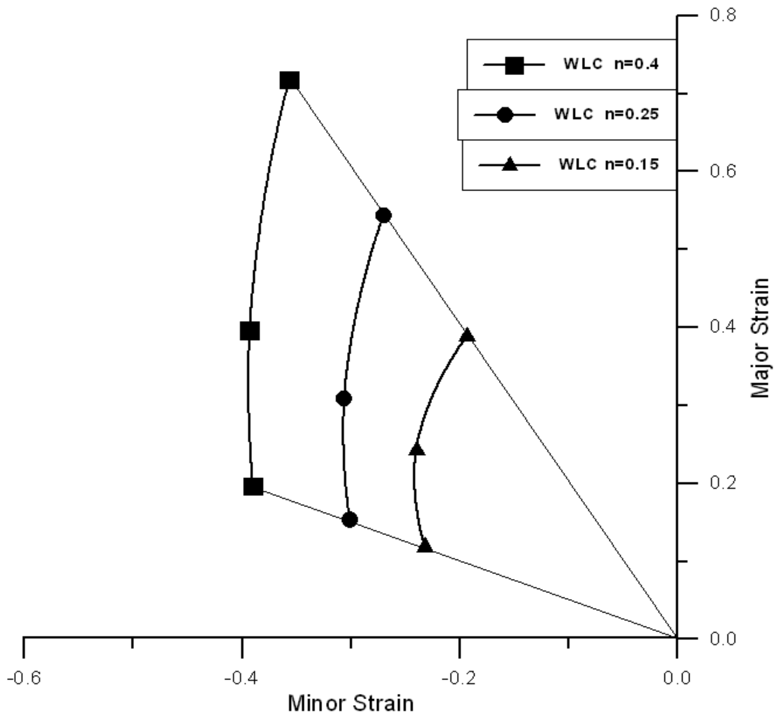

Fig .(6) Effect of strain hardening exponent on WLC

Figure(7)shows the effect of normal anisotropic ratio (R´ value) on the wrinkling limit diagram. It can be seen the limits of wrinkling limit curve increase while increase the normal anisotropic ratio.

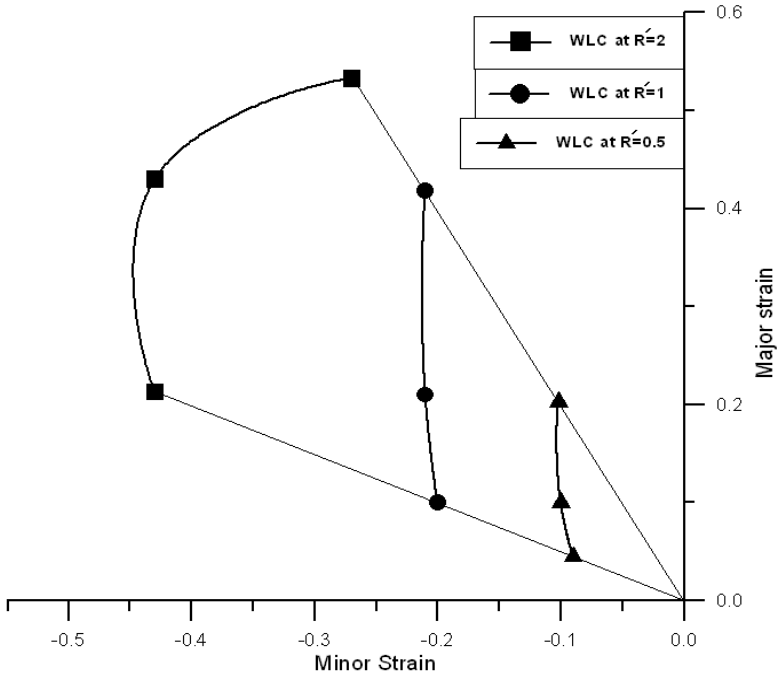

Fig .(7) Effect of normal plastic anisotropic ratio on WLC

Figure(8)shows the effect of imperfection factor (f value) on the wrinkling limit diagram. It can be seen the limits of wrinkling limit curve increase while increase the imperfection factor.

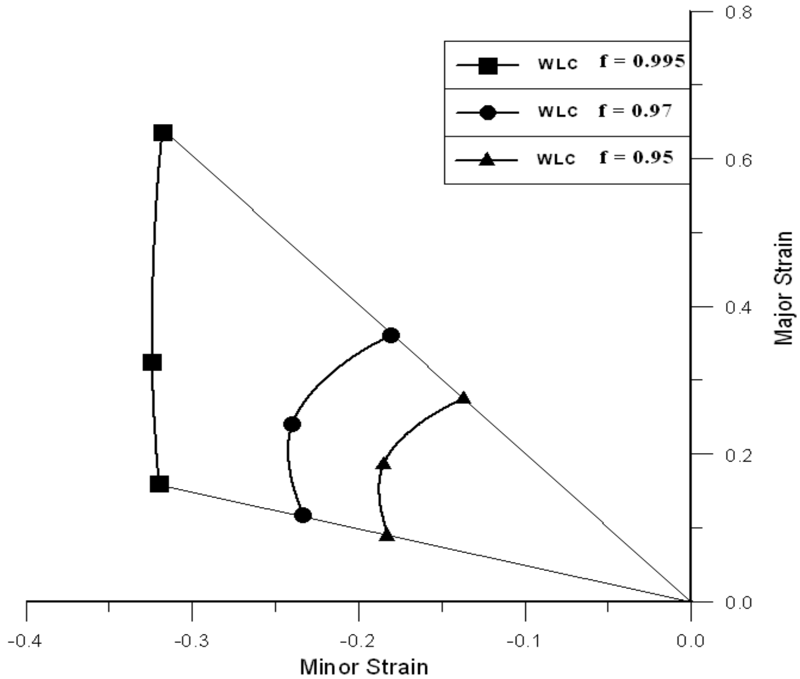

Fig .(8) Effect of imperfection factor on WLC

Figure(9)shows the effect of Strain rate sensitivity exponent (m value) on the wrinkling limit curve, . It can be seen the limits of wrinkling limit curve increase while increase the Strain rate sensitivity exponent .

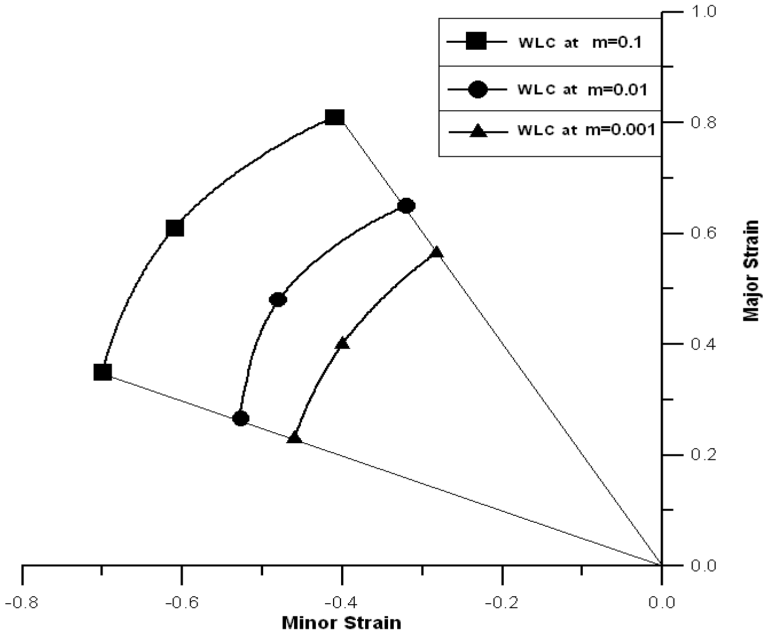

Fig .(9) Effect of Strain rate sensitivity exponent on WLC

Figure(10)shows the comparison of wrinkling limit curve between the aluminum and aluminum alloy sheets. It is shown that the highest wrinkling limit curve appeared in AA 5182 sheet and the lowest curve in aluminum alloy (AA 3103)sheet, AA 5182 sheet more resistance to wrinkling than all aluminum alloy sheets, because the AA 5182 sheet having high strain hardening exponent(n valve) comparing with aluminum sheet .

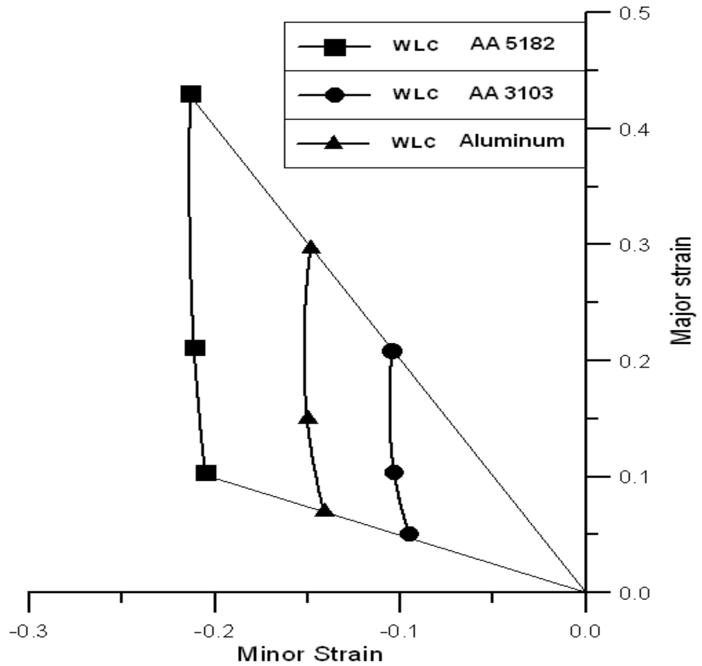

Fig .(10) Comparison of wrinkling limit curve between the aluminum and aluminum alloy(AA 3103, AA 5182) sheets

Figure(11)shows the comparison of wrinkling limit curve between the Steel , aluminum and aluminum alloy sheets. It is shown that the steel sheet more resistance to wrinkling than all sheets. because the steel sheet having high normal plastic Anisotropic ratio(R´)comparing with all aluminum alloy sheet .

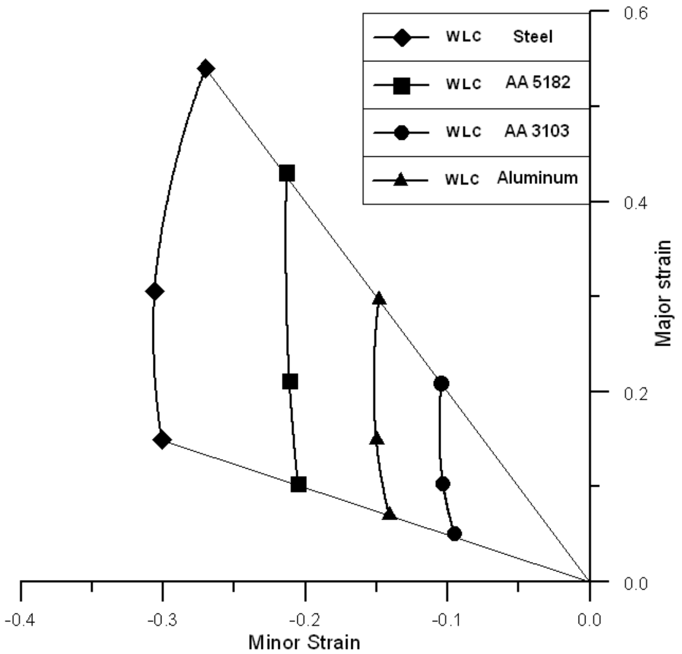

Fig .(11) Comparison of wrinkling limit curve between the steel, aluminum and aluminum alloy(AA 3103, AA 5182) sheets

5. Conclusions:

The major conclusions are listed below:

1) Wrinkling limit diagrams drawn in terms of strain with strain ratio(-0.5,-2) is highly suitable for the theoretical study of wrinkling behavior of sheet metals.
2) The onset of wrinkling depends on the factors , the strain hardening exponent, normal anisotropic ratio, Strain rate sensitivity exponent and imperfection factor improve the resistance sheet against wrinkling.
3) Steel sheet more resistance to wrinkling than aluminum and aluminum alloy sheets.

6. References:

1. **Ameziane-Hassani H, Neale KW. On the analysis of sheet metal wrinkling. Int. Journal Mech. Sci. 1991;33(1):13–21.**
2. **Balun T, Ling P, Lou MMK, Tsang SC. Detection and elimination of wrinkles on auto-body panel by the binder set analysis, SAE Tec. pap. series 930515; 1993.**
3. **Cao J, Boyce MC. Wrinkling behaviour of rectangular plates under lateral constraint. Int J Struct 1997;34(2):153–76.**

4. **Szacinzki AM, Thomson PF. Investigation of the existence of a wrinkling-limit curve in plastically-deforming metal sheet. J Mater Proc Tech 1991;25:125–37.**
5. **Karima M, Sowerby R. Report No. 144. Faculty of Engineering, McMaster University; 1980.**
6. **Narayanasamy R, Sowerby R. Wrinkling of sheet metals when drawing through a conical die. J Mater Proc Tech 1994;41:275–90.**
7. **Narayanasamy R, Sowerby R. Wrinkling behaviour of cold rolled sheet metals when drawing through a tractrix die. J Mater Proc Tech ,1995;49:199–211.**
8. **Di S, Thomson PF. Neural network approach for prediction of wrinkling limit in square metal sheet under diagonal tension. J Test Eval, JTEVA 1997;25(1):74–81.**
9. **Wang J, Wu X, Thomson PF, Flitman A. A Neural networks approach to investigating the geometrical influence on wrinkling in sheet metal forming. J Mater Proc Tech 2000;105:215–20.**
10. **Kim Y, Son Y ., J. Mater. Process. Technol. 97 (2000) 88–94.**
11. **Stafford, C.M., Harrison, C., Beers, K.L., Karim, A., Amis, E.J., Vanlandingham, M.R., Kim, H.-C., Volksen, W., Miller, R.D., Simonyi, E.: A buckling-based metrology for measuring the elastic moduli of polymeric thin films. Nat. Mater. 3, 545–550 (2004)**
12. **Chung, J.Y., Chastek, T.Q., Fasolka, M.J., Ro, H.W., Stafford, C.M.: Quantifying residual stress in nanoscale thin polymer films via surface wrinkling. ACS Nano 3, 844–852 (2009)**
13. **Burton, K., Taylor, D.L.: Traction forces of cytokinesis measured with optically modified elastic substrata. Nature 385, 450–454 (1997)**
14. **Harris, A.K., Wild, P., Stopak, D.: Silicone rubber substrata: a new wrinkle in the study of cell locomotion. Science 208, 177–179 (1980)**
15. **Kolaric, B., Vandeparre, H., Desprez, S., Vallee, R.A.L., Damman, P.: In situ tuning the optical properties of a cavity by wrinkling. Appl. Phys. Lett. 96, 043119 (2010)**
16. **Ohzono, T.,Monobe, H., Shiokawa, K., Fujiwara, M., Shimizu, Y.: Shaping liquid on a micrometre scale using microwrinkles as deformable open channel capillaries. Soft Matter 5, 4658–4664 (2009)**
17. **Hosford.W.F.,"On yield loci of anisotropic cubic metals.", Proc. 7th North American Metalworking Conference , S.M.E., Dearborn, MI, USA, pp. 191 (1979).**
18. **Marciniak, Z. and Kuczynski, K., Limits Strains in The Processes of Stretch-Forming Sheet Metal, Int. J. Mech. Sci .,vol. 9, pp. 609-620(1967) .**
19. **Narayanasamy .R ,Satheesh. J , Loganathan C," Effect of mechanical properties on wrinkling limit diagrams for Aluminum 5086 alloy annealed at different temperature ",J Mater Sci , 43:43–54 (2008).**