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An analytical study on forming limit curve of IF sheet metals of different grades

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ABSTRACT

Fracture is the major failure in sheet metal forming, and the selection of an appropriate material for a component still depends on designer's experience and trial and error. In order to ensure a component to be free from fracture, it is advantageous and gainful to use an analytical model to understand the influence of the material properties on the formability of the designed component before the component is put into production. The effect of the parameters m-value (yield equation constant), p - value (exponential parameter involved in r- value), and r-value (plastic anisotropic ratio or radius of curvature of the neck) on non-linear , linear Forming Limit Stress Curves (FLSCs) and Forming Limit Strain Curves (FLCs) are analysed using new yield equation for Interstitial – Free (IF) steels of different thickness. IF steel of thickness 0.6 mm is taken as IF steel (1) ,1.6 mm is taken as IF steel (2) and 0.85 (non-coated) is taken as IF steel (3) for convenience.

Introduction

The Forming- Limit Curve (FLC) is a very useful diagnostic tool for trouble shooting in sheet metal forming industries. A number of studies have been made to construct FLC for various sheet metals(Amit Kumar Gupta& D. Ravi Kumar(2006), N.V.Anbarasi(2008)). These methods generally lack simplicity and also have limitations in terms of applicability in an integrated computer modeling environment. The FLC depends on the pre-strain and the strain path. However, a FLSC is independent of the strain path, and FLCs can be derived from the FLSC for several strain paths.

IF steels have become important materials in the automotive industry due to their good press–shop performance. IF steels are made by adding titanium and / or niobium to the molten steel after degassing which offers excellent drawability. Since IF steels are free from interstitial elements namely carbon and nitrogen, these steels possess excellent ductility and formability. The low carbon steel sheets are widely used for automotive body applications. Aluminum alloys are used for body of the automobiles because of their light weight , and this helps in saving the fuel .The demand for vehicle safety makes the users prefer a material to increase the weight of the automobile body and crashing strength of the vehicle (Uenishi.A.,et al.(2003,2004)).

Previous researchers Rao K.P. [2001] and Sing W.M. [1997] have proved that the FLC established using FLSC methods, show a better accuracy in predicting the limit strain failures during sheet metal forming operation because of a close relationship between the FLSC method and plastic potential. The limit principal stresses namely σ_1 and σ_2 are to be determined.Using the flow-rule, the experimental parameters and sheet metal parameters ,namely the shape of the yield curve (m-value) and relative density and the forming limit curves for the various sheet metals are to be arrived.. Sing .W.M., ,Rao.K.P. (1993) and Stoughton,T.B., Zhu,X., (2004) have verified their FLSCs based on their formability prediction model and on the analytical influence of the basic material properties. They have also have measured their findings by tensile tests followed by development of linear limit yield stress locus.

In this paper, a new method of constructing FLCs is proposed in terms of readily measurable material properties from a tensile test . From the knowledge of a single limit yield stress , e.g., the maximum tensile stress, a limit yield stress curve can be determined, assuming that the material follows Hill's yield criterion and isotropic hardening model. The FLC can now be developed by using the Holloman strain- hardening equation .Hill's anisotropy yield criteria and the Levy-Mises equation.

Nomenclature

K-- Strength coefficient of material constant

n -- Strain hardening exponent.

m-- Yield Equation constant

R^N – Relative density (N=1.8-2.0)

r -- Plastic anisotropic ratio or radius of curvature of the neck.

p --- exponential parameter involved in r- value.

$\bar{\sigma}_L$ --- Equivalent limit stress.

$\bar{\sigma}$ ---- Equivalent stress.

σ_1, σ_2 -- Major and Minor true stresses

σ_u -- True tensile stress

σ_b --- Tensile stress

e --- Engineering strain.

$\bar{\varepsilon}$ --- Equivalent strain

$\varepsilon_1, \varepsilon_2$ --- Major and Minor true strain

$\bar{\varepsilon}_L$ --- Equivalent limit localised strain

$d\varepsilon_1, d\varepsilon_2$ --- Strain increments.

$\varepsilon_1^*, \varepsilon_2^*$ --- Limit Strains

$d\bar{\varepsilon}$ ---- Effective strain increment.

$\varepsilon_{1L}, \varepsilon_{2L}$,--- Major and Minor instability limit strains

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$d\lambda$ ---- Constant.

The aim of the present work is to determine FLC using FLSC curve by varying the various material parameters, using the generalized yield equation developed by Ponalagusamy et. al., [2007].

Mathematical Model for yield criteria :

It will be very useful in computer modeling if the FLSC can be constructed from readily measurable material properties such as σ_u, n, k and r in order that the FLCs can be drawn rapidly with less demand on experiments.

For plane – stress and an orthotropic and anisotropic material, the generalized yield criterion for slightly compressible anisotropic metal is given by:

$$f=\frac{\bar{\sigma}^2}{2\sigma_e^2}=\frac{1}{2\sigma_e^2}\left[\frac{2+R^N}{\left(2+r^p\right)\left(2+(p-1)^2\,r^p\right)}\right]\left[|\sigma_1|^m+|\sigma_2|^m+r^p\,|\sigma_1-\sigma_2|^m\right]^{2/m}\left[\left[\frac{3}{2+r^p}\right]^{2/m}\frac{\left(1-R^N\right)}{3}|\sigma_1+\sigma_2|^2\right] \quad \text{.....(1)}$$

For this case, the corresponding equivalent strain is obtained as.

$$\bar{\varepsilon}=\left[\frac{X_1}{1+2^{m-1}\,r^p}\right]^{(1/m-1)}\left[|\varepsilon_1|^{(m/m-1)}+|\varepsilon_2|^{(m/m-1)}\right]+\left[\frac{X_1}{2}\right]^{(1/m-1)}$$

$$\left[\left[1-\frac{1}{1+2^{m-1}\,r^p}\right]^{(1/m-1)}\right]\left[|\varepsilon_1+\varepsilon_2|^{(m/m-1)}\right]^{(m-1/m)} \quad \text{..(2)}$$

where $X_1=\left[\frac{(2+r^p)\left[2+(p-1)^2\,r^p\right]}{2+R^N}\right]^{(m/2)}$

Local Instability:

If ' f ' is the plastic function of the generalized yield criteria . The expressions for the limit strains ε_1^* and ε_2^* can be obtained as.

$$\varepsilon_1^*=\frac{(X+Z)}{X+Y+2Z}\,.\,n \quad \text{......(3)}$$

$$\varepsilon_2^*=\frac{(Y+Z)}{X+Y+2Z}\,.\,n \quad \text{.....(4)}$$

Where $X=\left(2+R^N\right)|\sigma_2|\,(2/m)\left[m|\alpha|^{m-1}+mr^p|\alpha-1|^{m-1}\right]$

$\bullet\, K_1/\left[\left(2+r^p\right)\,\left(2+(p-1)^2\,r^p\right)\right]$

$Y=\left(2+R^N\right)|\sigma_2|\,(2/m)\left[m-mr^p|\alpha-1|^{m-1}\right]$

$\bullet\, K_1/\left[\left(2+r^p\right)\,\left(2+(p-1)^2\,r^p\right)\right]$

and $Z=\left[\frac{3}{2+r^p}\right]^{2/m}\left(\frac{2}{3}\right)|\sigma_2|\left(1-R^N\right)|\alpha+1|$

where $K_1=\left[1+|\alpha|^m+r^p\,|\alpha+1|^m\right]^{(2/m)-1}$

$\alpha=\left(\sigma_1/\sigma_2\right)$

after calculating the pairs of ε_1^* and ε_2^* for various α, one can represent the associated FLC.

Using the Levy – Mises Flow Rule to find the limit strains :

Using the Levy-Mises Flow rule for plastic deformation, when the stresses or stress-ratio (σ_1/σ_2) is known, the corresponding strains can be found from the following relationship

$$d\varepsilon ij=\frac{\partial f\,(\bar{\sigma})}{\partial\sigma ij}d\lambda \quad \text{.....(5)}$$

where $d\lambda=d\bar{\varepsilon}\,/\left[\frac{df(\bar{\sigma})}{d\bar{\sigma}}\right]$ .....(6)

The instability strain is given by

$$d\varepsilon_1=\left[\frac{2+R^N}{(2+r^p)\left(2+(p-1)^2\,r^p\right)}\right]\bullet\left[|\sigma_1|^m+|\sigma_2|^m+r^p\,|\sigma_1-\sigma_2|^m\right]^{(2/m-1)}\bullet\left[|\sigma_1|^{m-1}+r^p\,|\sigma_1-\sigma_2|^{m-1}\right]+\left[\frac{3}{2+r^p}\right]^{2/m}\left[\frac{1-R^N}{3}\right]|\sigma_1+\sigma_2|\;\frac{d\lambda}{\sigma_e^2} \quad \text{......(7)}$$

$$d\varepsilon_2=\left[\frac{2+R^N}{(2+r^p)\left(2+(p-1)^2\,r^p\right)}\right]\bullet\left[|\sigma_1|^m+|\sigma_2|^m+r^p\,|\sigma_1-\sigma_2|^m\right]^{(2/m-1)}\bullet\left[|\sigma_2|^{m-1}-r^p\,|\sigma_1-\sigma_2|^{m-1}\right]+\left[\frac{3}{2+r^p}\right]^{2/m}\left[\frac{1-R^N}{3}\right]|\sigma_1+\sigma_2|\;\frac{d\lambda}{\sigma_e^2} \quad \text{......(8)}$$

where $d\lambda=\left[\frac{d\bar{\varepsilon}}{\bar{\sigma}}\right]\sigma_e^2$ .....(9)

and $K=\frac{\exp(n)}{n^n}(\sigma_b)$ .....(10)

The relationship between true tensile stress σ_u and tensile stress (σ_b) can be expressed as.

$$\sigma_u=\sigma_b(1+e) \quad \text{...(11)}$$

In case of anisotropic material, the critical localized strain is given by.

$$\varepsilon_{IL}=(1+r^p)\,n \quad \text{..(12)}$$

The equivalent limit stress for uniaxial tension can be obtained as.

$$\bar{\sigma}_L=K\left(\bar{\varepsilon}_L\right)^n \quad \text{......(13)}$$

Where $\bar{\varepsilon}_L$ is the equivalent limit – localized strain and is derived using equations (2) and (12).

Calculation of Limit Strains from Limit Stress:

The forming limit stress curve (FLSC) can be obtained from the uniaxial localized necking stress state. First, the true tensile stress σ_u is calculated from equation (11) and the value of K is calculated from (10). The uniaxial theoretical localized instability strain can be obtained using equation (12). From the result of equation (12), the equivalent limit stress at the localized neck is determined from equation (13).

From single limit yield stress, the FLSC can be determined by using the yield criterion equation (1). Since the FLSC is non-linear (or not a straight line), the linear regression method can be used to obtain the FLSC as a straight line. The equivalent stress corresponding to each point on the FLSC can be determined using equation (1) and the equivalent strain can be obtained using equation (2). Assuming a liner strain path, one can obtain the principal major and minor stains using equations (7), (8) and (9).

Results and discussion

Forming limit stress curve

The proposed method for predicting the forming limit curves has been tried out with generalized yield equation, by using the experimental values of σ_u , r and K that are available in Sathiya Narayanan, C. Ph.D., Thesis (2005), Narayanasamy R. (2007). The tensile test data obtained for the present work is shown in Table (1) for IF Steel. Mechanical properties of IF Steel of different grades are given in Table (2).

The effect of the parameter m on the variation of major principal stress with minor principal stress for IF Steel is shown in figures (1.1) to (1.3). It is observed that for a given value of minor principal stress, the major principal stress increases as the value of m increases. A careful observation of figures (1.1) to (1.3) shows that the upper most point of FLSC moves to the right side with an increase in m. Further the rate of increase or decrease in the variation of the major principal stress with the minor principal stress becomes predominant for the higher values of m. The foregoing characteristics may be attributed to the change in the shape of yield locus as the value of m increases.

The variation of major principal stress with respect to minor principal stress for different grades of IF Steel is shown in figure (1.3 a) .It is of interest to note that in the case of IF Steel (3), the major principal stress is higher than that of other IF Steel (1&2). Another important result is that IF Steel (3) shows better formability. It is pertinent to note that m - value has clear and predominant effect on FLSC in the case of IF Steel (3) when compared to that of other grades (1&2).

The effect of the parameter p on FLSC for IF Steel has been investigated in the present analysis. It is noticed from figures (1.4) – (1.6) that the point where the major principal stress attains its maximum value becomes stationary for different values of p. The most notable result of the present investigation is that the parameter p is a weak parameter in comparison with the parameter m, because it brings in less change on the FLSC.

From figure (1.3a), the variation of major principal stress with respect to minor principal stress for IF Steel is shown. IF Steel (3) shows better formability, for that r value is greater than 2 .For IF Steel (1) &(2) r value is less than 2 and their formability is less compared to IF Steel (3) .

Fig 1.1- Effect of m- value on FLSC for IF Steel(1)

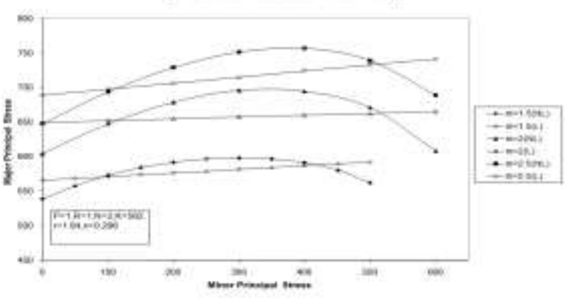


Fig 1.2 - Effect of m- value on FLSC for IF Steel(2)

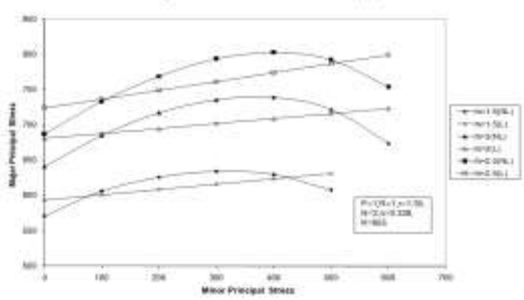


Fig 1.3 - Effect of m- value on FLSC for IF Steel(3)

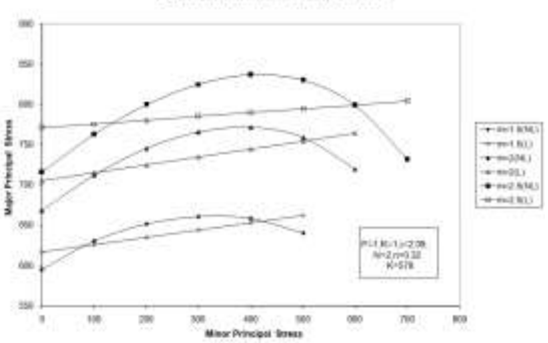


Fig 1.3(a)- Effect of r L value on Principal stress for different IF grades

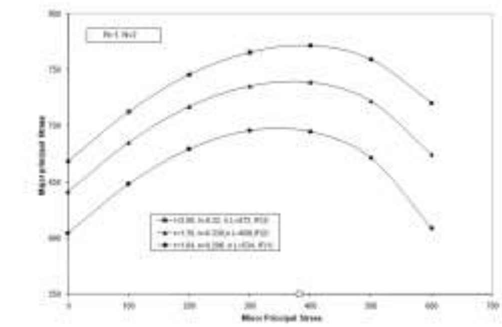


FIG-(1.4)- Effect of p value on Non-Linear and Linear FLSC for IF Steel (1)

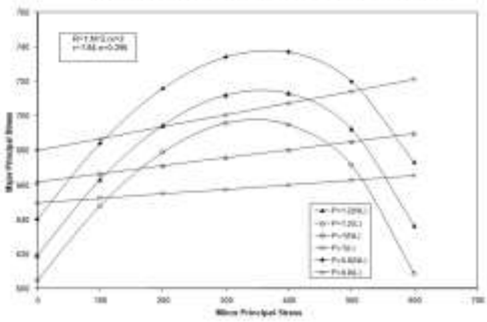


FIG - (1.5) - Effect of p value on Non - Linear and Linear FLSC for IF Steel(2)

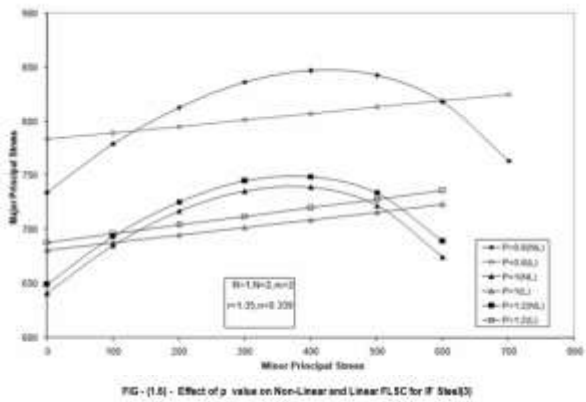
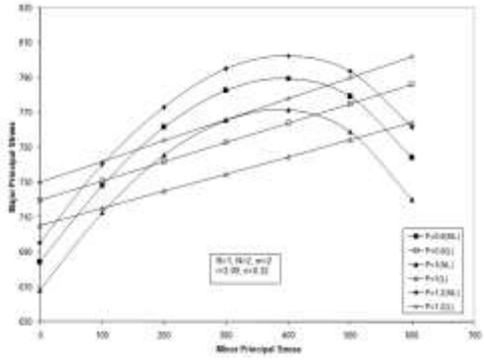


FIG - (1.6) - Effect of p value on Non-Linear and Linear FLSC for IF Steel(3)



Forming Limit Curve

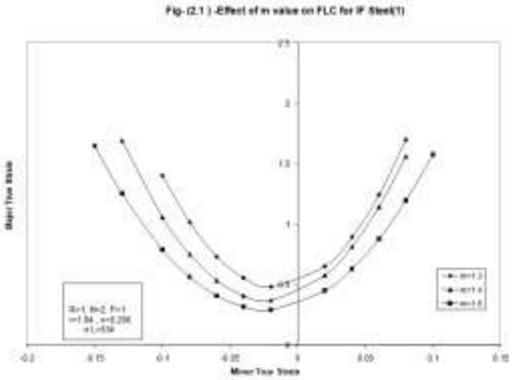
The attention of the present investigation is also focused on the effect of the parameter m on Forming Limit Curve (FLC) or Forming Limit Diagram (FLD) for IF Steel (1)- (3) from figures (2.1) – (2.3). For a given value of minor true strain, the major true strain decreases as the value of m increases. It is of interest to mention that the effect of the parameter m on FLC becomes predominant when the value of minor true strain is negative but it is less predominant as the value of minor true strain is positive. It is noteworthy that as the value of m increases, the point of the FLC at which the major principal strain attains its minimum, moves bottom downward and towards the left side.

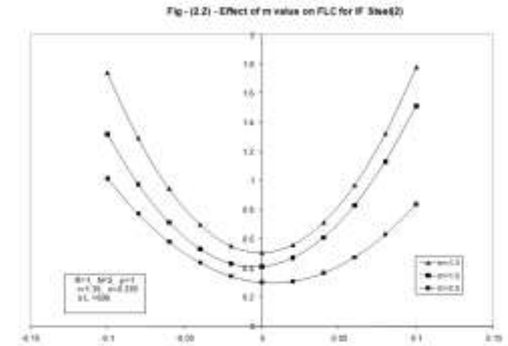
From figure (2.4) IF steel (3) has better formability than IF steel (1) &(2).The value of r is greater greater than 2 for IF steel (3) and it is less than 2 for IF steel (1) &(2).

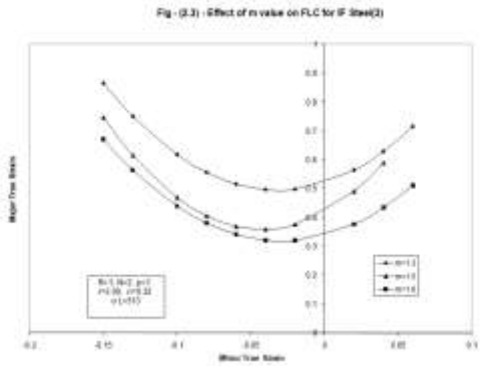
The effect of p value on FLC for If steel (1)-(3) from fig (2.5 -2.7) are investigated . The increase or decrease of p value does not change the FLC . So p is a weak parameter compared to m.

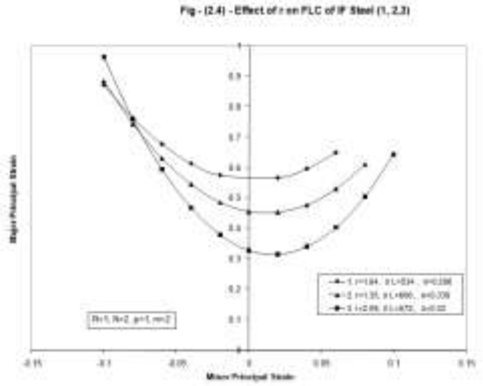
Conclusion:

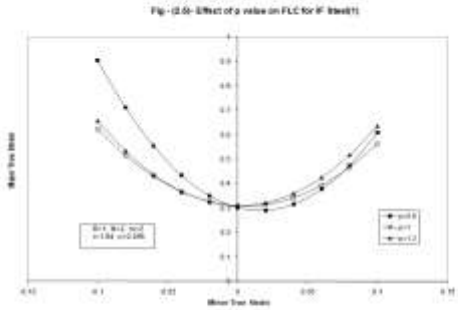
Hence it is concluded that the yield criterion constants m value, r- value and p-value have effect on the formability of sheet metals.

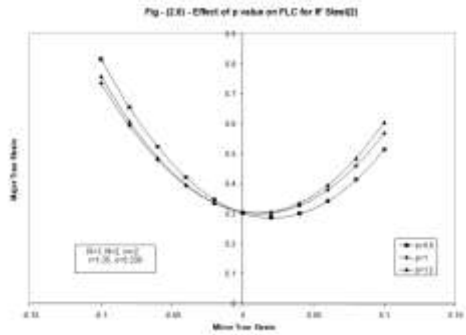












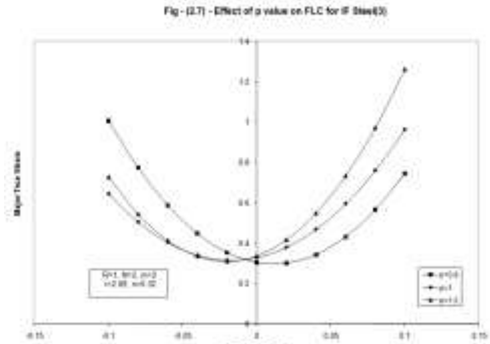


Fig - (2.8) – Effect of m value on FLC for IF Steel (1,2,3)

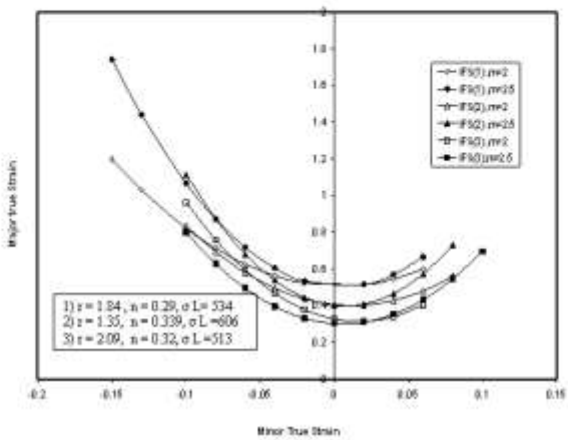


Table: 1 –Mechanical Properties of IF steels Tested

Sheet metal thickness	r	$\bar{\sigma}_L$	n	K
1 – 0.6 mm	1.84	534	0.296	562
2 – 1.6 mm	1.35	606	0.339	655
3 – 0.85 mm (non –coated)	2.09	572	0.32	578

Table: 2

Mechanical properties of IF Steel used for verifying the new methodology for obtaining the FLCs.

IFS	K Mpa	$\bar{\sigma}_L$ Mpa	R	p	r	n	N	m
1	562	534	1	1	1.84	0.296	2	1.5
	562	534	1	1	1.84	0.296	2	2.0
	562	534	1	1	1.84	0.296	2	2.5
	562	534	1	1	1.84	0.296	2	3.0
2	655	606	1	1	1.35	0.339	2	1.5
	655	606	1	1	1.35	0.339	2	2.0
	655	606	1	1	1.35	0.339	2	2.5
	655	606	1	1	1.35	0.339	2	3.0
3	572	578	1	1	2.09	0.32	2	1.5
	572	578	1	1	2.09	0.32	2	2.0
	572	578	1	1	2.09	0.32	2	2.5
	572	578	1	1	2.09	0.32	2	3.0

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