Numerical and Analytical Investigation of the Sandwich Sheet Rolling Process Considering Coulomb Friction

V. Alimirzaloo*
Engineering Department, Urmia University, Urmia, Iran
E-mail: v.alimirzaloo@urmia.ac.ir
*Corresponding author

Received: 14 January 2015, Revised: 30 February 2015, Accepted: 31 May 2015

Abstract: The rolling process is an economic and efficient approach for production of the sandwich sheets. In this research sandwich sheet rolling process is investigated using an analytical method (slab method) and a numerical approach (finite element method). Rigid-perfect plastic material behaviour and coulomb friction model were used in both analysing approaches. Because of the plain strain condition, the process is analysed as 2-dimentioal problem. The horizontal stress distribution in the layers, the rolling pressure along the contact interface and the neutral point between the roll and the sheet are investigated. Then the effects of the process parameters such as friction between the sheet and the roll, shear yield stress ratio of the matrix and clad layers, front and back tensions on the rolling characteristics such as the pressure and neutral point position are studied. The results demonstrate that the finite element method results are very near to the slab method results and extra simplifying assumptions in the slab method cause low deviation in the results. In both methods as the friction coefficient increases, the rolling pressure increases and the neutral point approaches the entrance of the roll gap. As the shear yield stress ratio increases, the rolling pressure increases but the neutral point is not shifted. As the front or back tensions are applied on the sandwich sheet, the rolling pressure decreases and the neutral point is shifted inverse of the tensions direction.

Keywords: Sandwich Sheet, Rolling, Finite Element Method, Slab Method

Reference: V. Alimirzaloo, "Numerical and Analytical Investigation of the Sandwich sheet Rolling Considering Coulomb Friction", Int J of Advanced Design and Manufacturing Technology, Vol. 8/No. 3, 2015, pp.43-54

Biographical notes: Vali Alimirzaloo was born in 1978. He received his PhD in Mechanical Engineering from Amirkabir University of technology in 2011. He is currently Assistant Professor at the Department of Engineering, Urmia University, Urmia, Iran. His current research interest includes die design and analysis of metal forming processes.

1 INTRODUCTION

Sandwich sheets possess advantages such as high strength to weight ratio, corrosion resistant and high electrical conductivity. Therefore, they are widely used in the industries. Furthermore, one of the techniques for decreasing the rolling force in conventional rolling of high strength materials is rolling them between the layers of soft metals which is known as the sandwich rolling. Up to now, researchers have studied the sandwich sheet rolling process by experimental and theoretical methods. Hwang et al., [1] studied the deformation behaviour of the layers in the sandwich sheet rolling using stream function method and experiments by employing aluminium, mild steel and stainless steel as layers of the sheets. They concluded that the theoretical predictions of the thickness ratio of the rolled sheets and rolling force are in good agreement with the experimental results.

In other research Hwang et al., [2] investigated plastic instability occurring in the hard inner layer during the sandwich rolling. The proposed plastic instability criteria were useful in designing the pass-schedule of sandwich sheet rolling processes. Also they [3] investigated the bonding behaviour at the roll gap of the sandwich sheets during the process using analytical method and experiments. Lin et al., [4-5] investigated hot rolling of the sandwich sheet with the copper core and aluminium layers by the finite element method (FEM). G. Y. Tzou [6] analyzed the sandwich rolling process using slab method by considering coulomb friction model. They achieved relations for the normal and shear stresses, rolling pressure and force, rolling torque and neutral point position. His analytical model was able to offer systematic knowledge about the sandwich sheet rolling process.

G. Y. Tzou et al., [7] developed an analytical approach to the cold and hot bond rolling of sandwich sheet with outer hard and inner soft layers. The bonding conditions of the unbounded sandwich sheet were found to avoid the failure in bond rolling. Harada et al., [8] experimentally studied the sandwich rolling of sintered compacts of pure chromium using mild steel sheets as clad layers. They demonstrated that the sandwich rolling prevents the occurrence of surface cracks, since the sheets on both sides interrupt the temperature decrease of the surfaces, where this method increases the workability of the chromium.

M. N. Huang et al., [9] investigated the effect of the friction models (coulomb and shear friction) in analyzing the sandwich sheet rolling process by the slab method. The relationships between the frictional coulomb coefficient and shear friction factor under rolling condition were derived. Daneshmanesh et al., [10] proposed a mathematical model for the sandwich sheet rolling process using the upper bound method and verified their analytical results by conducting the experiments by employing aluminium, mild steel and copper as the layers of the sandwich strips. They found good agreement between the theoretical predictions and experimental results.

Arabi et al., [11] investigated the interface region of a tri-layer sandwich composite from the sheets of brass-steel-brass. They found optimum conditions for the production of the composite by mathematical modelling and simulation. Kim et al., [12] studied the production of the thin gauge bulk metallic glass (BMG) sheets by the sandwich rolling of thick Zr-based BMG plates between upper and lower outer copper sheets. They disclosed that the sandwich rolling with thick outer sheets minimized the shear strains leading to a strain state close to the plane strain in the rolled BMG sample. Analysing the sandwich sheet rolling process using the slab method is able to predict the process parameters such as the stress distributions and rolling pressure.

Due to the process complications in this method, simplifying geometrical and mechanical assumptions were required to be made. These assumptions initiated theoretical results to be different than the actual results. In the numerical methods such as the finite element method, some of these assumptions may be eliminated. Besides the finite element method is a numerical technique for finding approximate solutions to the boundary value problems. It seems notable that the sandwich rolling process is investigated by both approaches and compared, where up to now, this comparison has not been done. In this research the sandwich sheet rolling process is investigated and compared using the slab method as an analytical approach and FEM as a numerical method.

2 SLAB METHOD

Slab method (SM) formulation of the sandwich sheet rolling process has been presented by G. Y. Tzou [6]. Fig. 1 shows the schematic diagram and geometrical parameters of the sandwich sheet rolling process. The subscripts i and o in the variables represent the input and output of the rolls and the subscripts c and m represent the clad and matrix sheets respectively, where the radius and speed of the rolls are identical. To simplify the formulation of the SM, the following assumptions are made:

1-The roll radius to sheet thickness ratio is large and contact arc of the roll is much smaller than the circumference of the roll.

2-Stresses are distributed uniformly within the slab. The vertical and horizontal components of the stresses are regarded as principal stresses.

3-The deformation of the sheets is plain strain.

4-Coulomb friction model ($\tau = \mu p$) governs between the contact surfaces. Friction coefficient is constant.

5-The rolls are rigid and the sheets are rigid-perfect plastic.

6-There is no sliding between the clad and the matrix layers.

In the plastic deformation region there is a point known as the neutral point (x_n) where the friction force between the rolls and the sheet is inverted. Therefore, deformation region is divided in two zones: before the neutral point (zone I) and after the neutral point (zone II).

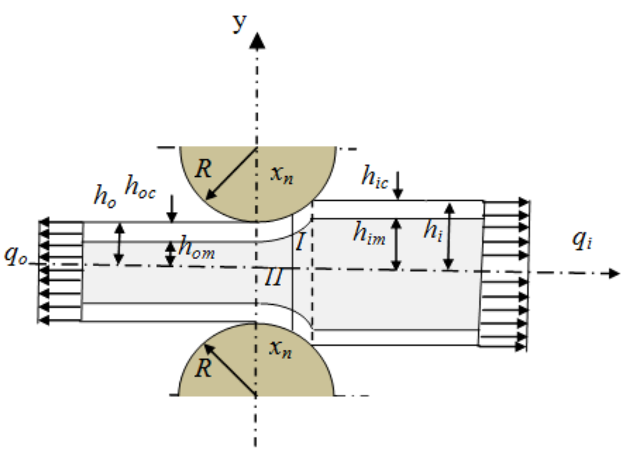

Fig. 1 Schematic illustration and geometrical parameters of the sandwich rolling process

Because of the slab symmetry, only half of the slab is considered for analyses. Fig. 2 shows the slab stress state of half-sandwich sheet in zone I. Equilibrium equations in both the layers can be summarized as:

$$\frac{d(h_c q_c)}{dx} + p_c tan\theta_c - p_m tan\theta_m - \tau_c + \tau_m = 0 \qquad (1)$$

$$p = p_c + \tau_c tan\theta_c \qquad (2)$$

$$\frac{d(h_m q_m)}{dx} + p_m tan\theta_m - \tau_m = 0 \qquad (3)$$

$$p = p_m + \tau_m tan\theta_m \qquad (4)$$

Where h, p and q are half thickness of the sheet, vertical stress and horizontal stress respectively. θ_c and θ_m are the contact angle, τ_m and τ_c are the friction shear stress between the surfaces clad-matrix and clad-roll respectively. p_c and p_m are the rolling pressure and pressure between the layers respectively. Von Misses criteria for the plain strain condition in the sheet is:

$$p + q_c = 2k_c \qquad (5)$$

$$p + q_m = 2k_m \qquad (6)$$

Where

$$k_c = \frac{\sigma_{yc}}{\sqrt{3}} \;, \quad k_m = \frac{\sigma_{ym}}{\sqrt{3}}$$

σ_{yc} and σ_{ym} are the mean yield stress in the clad and matrix sheets. By assuming that the contact arc of the roll is much smaller than the circumference of the roll, some geometrical relations can be achieved as below:

$$h = h_c + h_m = h_0 + \frac{x^2}{2R} \;, \quad \frac{dh}{dx} = \frac{x}{R} \;, \quad tan\theta_c = \frac{x}{R} \qquad (7)$$

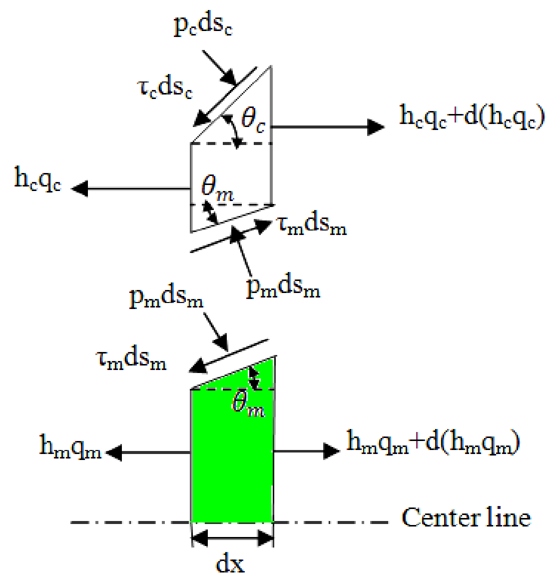

Fig. 2 Stresses of half sandwich sheet in zone I

By substituting equations (5), (6), and (7) into equations (1)-(4) and solving the resultant equation using the boundary conditions, specific rolling pressure $\left({}^{p}/_{2k_c}\right)$ for each of the regions can be obtained as [6]:

Zone I ($x_n \le x \le L$) :

$$\frac{p}{2k_c} = \left[f_i - \frac{2\alpha}{a_1}\left(\frac{\omega_i^3}{3} - \frac{\omega_i^2}{a_1} + s_1\omega_i - t_1\right)\right] e^{a_1(\omega_i - \omega)} + \frac{2\alpha}{a_1}\left(\frac{\omega^3}{3} - \frac{\omega^2}{a_1} + s_1\omega - t_1\right) \qquad (8)$$

Zone II ($0 \le x \le x_n$) :

$$\frac{p}{2kc}=\left(f_o+\frac{2\alpha t_2}{a_2}\right)e^{-a_2\omega}+\frac{2\alpha}{a_2}\left(\frac{\omega^3}{3}-\frac{\omega^2}{a_2}+s_2\omega-t_2\right) \quad (9)$$

Where

$$a_1=\mu\sqrt{2R/h_o}\,,\qquad a_2=-\mu\sqrt{2R/h_o}$$

$$t_1=\frac{1}{a_1}+\frac{2}{a_1^3},\quad s_1=1+\frac{2}{a_1^2},\qquad t_2=\frac{1}{a_2}+\frac{2}{a_2^3},\quad s_2=1+\frac{2}{a_2^2}$$

$$\omega=\tan^{-1}(x/\sqrt{2Rh_o}),\qquad \omega_i=\tan^{-1}(L/\sqrt{2Rh_o})$$

$$\beta=\frac{h_c}{h}=\frac{h_{ic}}{h_i}=\frac{h_{oc}}{h_o}$$

$$\alpha=\beta+\frac{k_m}{k_c}(1-\beta)$$

$$f_i=\alpha-\frac{q_i}{2k_c},\qquad f_o=\alpha-\frac{q_o}{2k_c}$$

By substituting equations (8) and (9) into the relations (5) and (6), specific horizontal stresses $\frac{q_m}{2k_m}$ and $\frac{q_c}{2k_c}$ can be found.

3 FINITE EKEMENT METHOD

FE analysis of the sandwich sheet rolling process was done using the dynamic explicit analyzer of the ABAQUS software. Because of the plain strain condition and asymmetry of the process, half of the process as 2-dimentioal problem was analyzed (Fig. 3). 4-node break element was used for meshing the sheet. The rolls considered rigid bodies, where the rolling conditions are:

Roll radius: 100mm
Total thickness of the initial sheet (2hi): 3 mm
Total thickness of the sheet after rolling (2hi): 1.8 mm
Shear yield stress of the clad sheet (kc): 98.1MPa
Thickness ratio of clad to the matrix sheet (β):0.2 mm

For investigating the process parameters, effect of the shear yield stress ratio of the matrix to the clad (km/kc), friction coefficient and tension stresses on the rolling pressure were studied. These parameters were tacked as:

Shear yield stress ratio of the matrix to the clad sheet (km/kc):0.5, 1, 2
Friction coefficient (μ): 0.1, 0.15, 0.2
Tension stresses (according to Fig. 1):

qi=qo=0
qi=0, qo=kc/2
qi=kc/2, qo=0
qi=qo=kc/2

Fig. 3 FE model

4 RESULTS AND DISCUSSION

Using the magnitude of the parameters in section 3.2, pressure and stresses from the SM relations ((8), (9)) are obtained. Then the results of the FEM and SM are compared and discussed. Fig. 4 Shows the FE simulation of the sandwich sheet rolling process where process conditions are μ= 0.15, km/kc=2, qi=qo=0.

Fig. 4 FE simulation of the sandwich sheet rolling process

Fig. 5 shows the distribution of the vertical stress in the rolling gap. It is observed that the vertical stress doesn't vary in the vertical direction however it varies in the horizontal direction. The horizontal stress is compressive and distributed uniformly in the clad and matrix sheets, where the vertical Stress distribution in the clad and matrix sheets is similar.

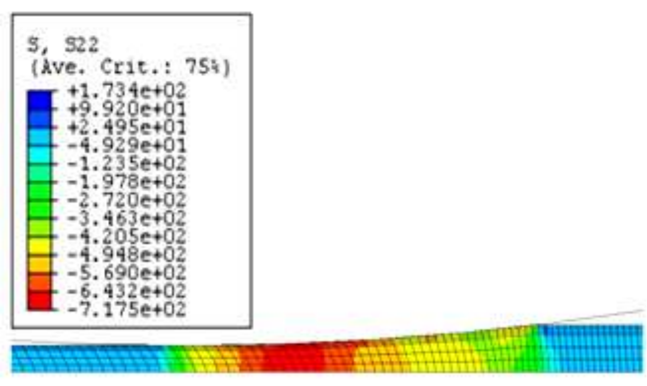

Fig. 5 Vertical stress distribution in the roll gap

Fig. 6 shows the variation of the specific pressure in the rolling gap by the SM analysis and FEM. It is observed that the rolling pressure variation in both methods is similar. SM result is slightly lower than the FE result. It is due to the simplifying assumptions in the SM such as uniformly distribution of the stresses within the slab and contact arc of the roll which is much smaller than the circumference of the roll.

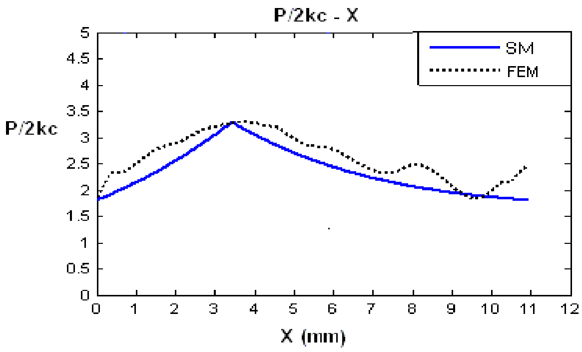

Fig. 6 Specific pressure in the rolling gap by the SM and FEM

Fig. 7 shows the distribution of the horizontal stress in the rolling gap. Unlike the vertical stress, horizontal stress distribution in the clad and matrix sheets is not similar. This stress is compressive in the clad sheet however; it is tensional and compressive in the matrix sheet. It is observed that the stresses are distributed uniformly on each sheet. Therefore, the assumption of uniformly distribution of the horizontal stress within the slab in SM analysis is nearly acceptable.

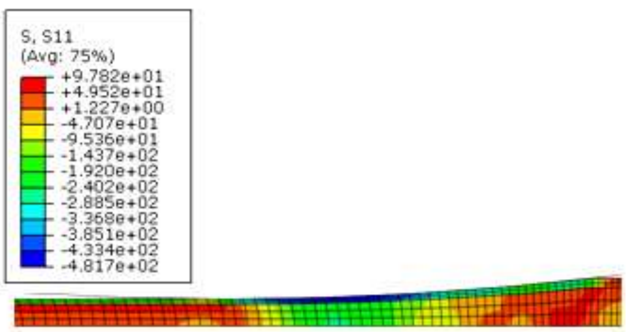

Fig. 7 Horizontal stress distribution in the roll gap

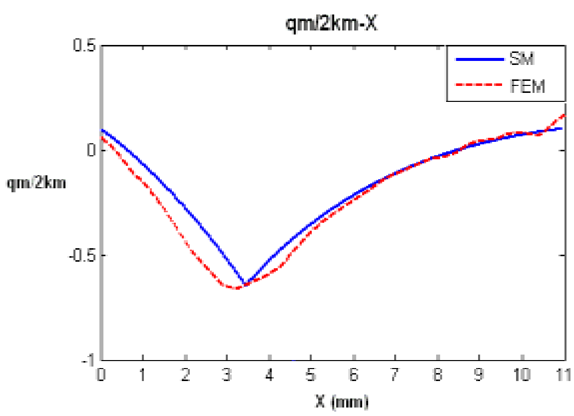

Fig. 8 Specific horizontal stress in the rolling gap for the matrix

Figs. 8 and 9 show the variation of the specific horizontal stress in the rolling gap for the clad and matrix sheets respectively. Similarity of the stress variation in both methods is observed. Because of the simplifying assumptions in the SM, its result is slightly lower than the FE result. Furthermore it is observed that in both methods, specific horizontal stress in the clad is compressive whereas in the matrix, it is tensile in the entrance and exit of the roll gap and it is compressive inside the roll gap.

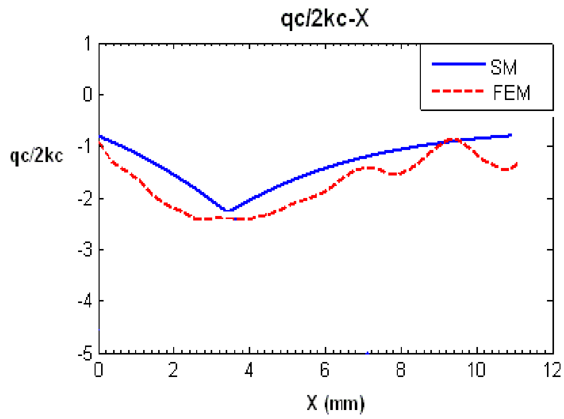

Fig. 9 Specific horizontal stress in the rolling gap for the clad

According to the Eqs. (8) and (9), several parameters have effect on the specific rolling pressure. Figs. 10 and 11 demonstrate the effect of the friction coefficient (μ) on the rolling pressure using the SM and FEM respectively. It is observed that the rolling pressure increases as μ increases in both the methods. Furthermore, in the SM, as μ increases, the neutral point approaches the entrance of the roll gap. However, it is not quite obvious in the FEM.

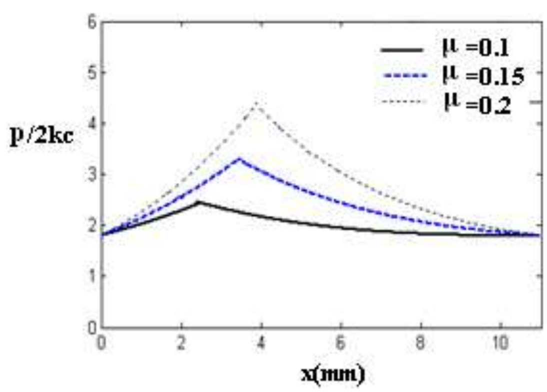

Fig. 10 Friction coefficient effect on the rolling pressure using SM

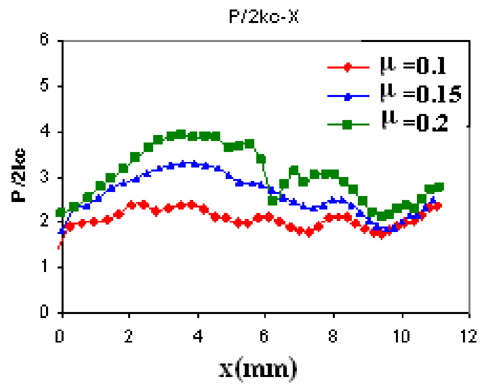

Fig. 11 Friction coefficient effect on the rolling pressure using FEM

Figs. 12 and 13 demonstrate the shear yield stress ratio effect on the specific rolling pressure using the FEM and SM respectively. It is observed that the rolling pressure increases as the shear yield stress ratio increases in both methods. Furthermore neutral point is not shifted as the shear yield stress ratio increases.

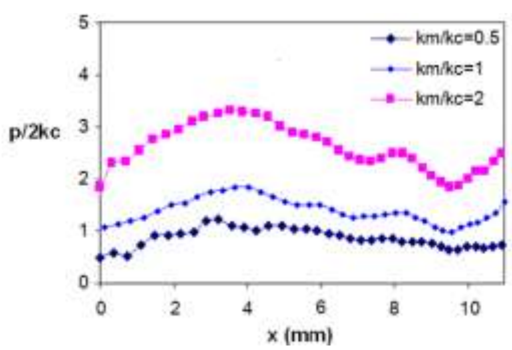

Fig. 12 Shear yield stress ratio effect on the specific rolling pressure using FEM

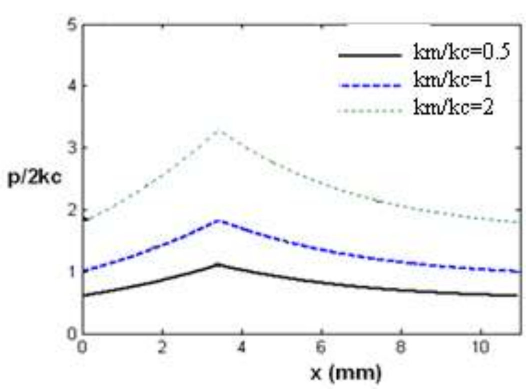

Fig. 13 Shear yield stress ratio effect on the specific rolling pressure using SM

Figs. 14 and 15 show the front and back tensions effect on the specific rolling pressure in the FEM and SM respectively. It is observed that the rolling pressure decreases as the front or back tensions are applied on the sandwich sheet in both methods. Furthermore, in the SM (Fig. 15) the neutral point is transmitted back when the front tension is applied and it is transmitted to the front when the back tension is applied. This is not perfectly obvious in the FEM (Fig. 14).

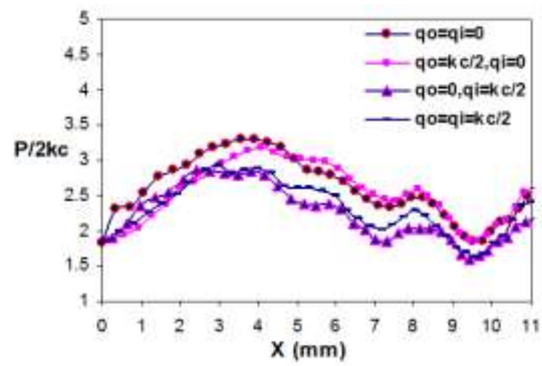

Fig. 14 Front and back tensions effect on the specific rolling pressure using FEM

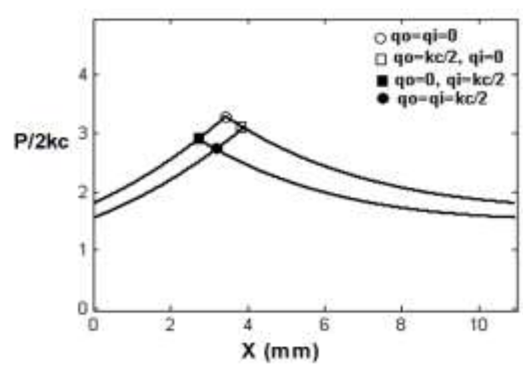

Fig. 15 Front and back tensions effect on the specific rolling pressure using SM

5 CONCLUSION

Sandwich sheet rolling process is investigated using an analytical method (i.e. SM) and a numerical method (i.e. FEM). The results of the study can be concluded as:

1- Stress distribution in the rolling gap shows that the vertical and horizontal stress variation in the vertical direction is very low and it can be negligible. Therefore the assumption of uniform distribution of the stresses in the vertical direction within the slab in the SM analysis is nearly acceptable.

2- The rolling pressure and horizontal stress variation in the SM and FEM is similar. The SM result is slightly lower than the FEM result. It could be due to the simplifying assumptions in the SM.

3- Investigation of the parameters effects such as friction coefficient, shear yield stress ratio and tension stresses, demonstrates that their effects on the rolling pressure in the SM and FEM methods are similar. As the friction coefficient increases, the rolling pressure increases and the neutral point approaches the entrance of the roll gap. As the shear yield stress ratio increases, the rolling pressure increases but the neutral point doesn't displace. As the front or back tensions are applied on the sandwich sheet, the rolling pressure decreases and the neutral point is shifted inverse of the tension direction.

4- Finite element method results are very near to the slab method results and extra simplifying assumptions in the slab method cause slight deviance in the results.

REFERENCES

[1] Hwang, Y. M., Hsu, H. H., and lee, H. J., "Analysis of sandwich sheet rolling by stream function method", Int. J. Mech. Sci., Vol. 37, No. 3, 1995, pp. 297-315.

[2] Hwang, Y. M., Hsu, H. H., and lee, H. J., "Analysis of plastic instability during sandwich sheet rolling", Int. J. Mach. Tools Manufact., Vol. 36, No. 1, 1996, pp. 47-62.

[3] Hwang, Y., M., Hsu, H. H., and Hwang, Y. L., "Analytical and experimental study on bonding behavior at the roll gap during complex rolling of sandwich sheets", Int. J. Mech. Sci., Vol. 42, 2000, pp. 2417-2437.

[4] Lin, Z. C., Huang, T. G., "Hot rolling of an aluminum-copper sandwich at strip with the three-dimensional finite element method", J. Mat. Proc. Tech. Vol. 99, 2000, pp. 154-168.

[5] Lin, Z. C., Huang, T. G., "Different degree of reduction and sliding phenomenon study for three-dimensional hot rolling with sandwich flat strip", Int. J. Mech. Sci., Vol. 42, 2000, pp. 1983-2012.

[6] Tzou, G. Y., "Theoretical study on the cold sandwich sheet rolling considering Coulomb friction", J. Mat. P., Vol. 114, 2001, pp. 41-50.

[7] Tzou, Y., Tieu, A. K., Huang, M. N., Lin, C. Y., and Wu, E. Y., "Analytical approach to the cold and hot bond rolling of sandwich sheet with outer hard and inner soft layers", J. Mat. Proc. Tech. Vol. 125-126, 2002, pp. 664-669.

[8] Harada, Y., Ohmori, M., "Sandwich rolling of sintered compacts of pure chromium", J. Mat. Proc. Tech. Vol. 137, 2003, pp. 117-122.

[9] Huang, M. N., Tzou, G. Y., and Syu, S. W., "Investigation on comparisons between two analytical models of sandwich sheet rolling bonded before rolling", J. Mat. Proc. Tech., Vol. 140, 2003, pp. 598-603.

[10] Daneshmanesh, H., Karimitaheri, A., "Theoretical and experimental investigation of cold rolling of tri-layer strip", J. Mat. Proc. Tech., Vol. 166, 2005, pp. 163-172.

[11] Arabi, H., Seyedein, S. H., and Mehryab, A., "Tolaminejad, B., Mathematical modeling and simulation of the interface region of a tri-layer composite material, brass-steel-brass, produced by cold rolling", International Journal of Minerals, Metallurgy and Materials, Vol. 16, No. 2, 2009, pp. 189-196.

[12] Kim, H. J., Bae, J. C., Park, E. S., Huh, M. Y., and Kim, D. H., "Production of Zr-based bulk metallic glass thin strips by means of sandwich rolling in the super cooled liquid region", J. Alloys and compounds, Vol. 504S, 2010, pp. S271-S274.