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Finite Element Analysis of Deformation Behavior of Wire Cold Flat Rolling

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Abstract

Flat rolling of wire is an industrial process used to manufacture electrical flat wire, medical catheters, springs and piston segments, among other products. This paper presents a 3D finite element analysis of wire flat rolling. The variations of rolling force due to roll speed changes, Effect of reduction in height on width of contact Area, and Lateral spread of wire has been discussed. It is found that a negligible increase in flow stress and rolling force does occur due to increase in the strain rate at room temperature. Besides, the results showed that the behavior of rolling force variation versus roll speed depends on the rolling reductions. A theoretical relationship has been developed to relate the reduction in height of wire to the width of contact area between the rolls and wire. This relationship depicts that the width of contact area is proportional to square root of reduction in height of wire. Finally the finite element can give a reasonable estimation of the deformation behavior in wire flat rolling, since the theoretical predictions are reasonable agreement with the experimental measurements of other authors.

Keywords: wire flat rolling, wire cold rolling

تحليل سلوك التشوه لعملية درفلة الاسلاك باستخدام طريقة العناصر المحددة

الخلاصة

تعتبر الدرفلة المستوية للاسلاك عمليةُ صناعيةُ تستعمل في الصناعات الكهربائية والطبية وفي صناعة النوابظ واجزاء المكبس . هذا العمل يقدم تحليل ثلاثي الابعاد باستخدام طريقة العناصر المحددة لعملية الدرفلة المستوية للاسلاك. تم دراسة تاثير التغير في سرعة الدرفلة على قوة الدرفلة ، تاثير النقصان في الارتفاع على عرض مساحة التلامس، والتشوه الجانبي للسلك. اوضحت النتائج وجود زيادة طفيفة في اجهاد الانسياب وان السبب في زيادة قوة الدرفلة يعود الى الى الزيادة الملحوظة في معدل الانفعال في درجة حرارة الغرفة. إضافةً إلى ذلك، لوحظ ان قوةِ الدرفلة عند سرع درفلة مختلفة يَعتمدُ على مقدار التخفيض في الارتفاع. تم استنباط علاقة رياضية نظرية تفسر العلاقة بين مقدار التخفيض في قطر السلك وعرض مساحة التلامس بين السلك والدرفيل. من خلال هذه العلاقة وجد ان عرض مساحة التلامس يتناسب طرديا" مع الجذر التربيعي للتخفيض في ارتفاع السلك. بينت النتائج المستنبطة من نظرية العناصر المحددة ان هنالك توافق مقبول في تخمين سلوك التشوة لعملية درفلة الاسلاك مقارنة مع نتائج عملية لباحثين اخرين.

كلمات مرشدة: درفلة المستوية للاسلاك ، درفلة الاسلاك على البارد

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1. Introduction

The rolling process is one of the most popular processes in manufacturing industries in that almost 80% of metallic equipment has been exposed to rolling, at least one time in their production period. Among all kinds of the rolling processes, the flat rolling is the most practical one. In industrial countries, about 40–60% of rolling products are produced with this type of rolling. Therefore, many scientists have tried to enhance the quality and quantity of products by optimizing this process and identifying parameters affecting it to satisfy their customers. Flattened wires are widely used in saw blades, spring, piston rings and transformer industries. These wires are produced by the process of flat rolling, see Fig.(1). In this process, wire of circular cross section is cold rolled between two flat rolls in one or several passes to achieve the desired thickness to width ratio [1]. Finite element models have been used to analyze a number of metal-forming processes [2]. However, few models have been developed to simulate flat roll-forming processes. These processes present many computational challenges to finite element analysis. One difficulty is that full-length die contours must be modeled since the stressed area of the die changes as the forming operation progresses. Another difficulty is that nodal coordinates must be updated constantly because the blanks rotate and translate at the same time. Additionally, friction and slippage between the dies and the workpiece must be considered.

Finally, very high mesh densities are required because of the massive three-dimensional material flow in the blanks.

These flat rolling characteristics increase the number of calculations at each step of the simulation.

An empirical formula for determining spread in flat rolling process was proposed and applied by Wusatowki[3], Based on Wusatowski's work, Mauk[4] has proposed the iteration method, and Bursal et al.[5] have used the vertical slab method for analysis. More general empirical formulas for various rolling shapes were proposed by Saito et al.[6,7] and Shinokura and Takai[8,9] by combining the experimental results shape rolling and spread formula for flat rolling.

The flat rolling of wire combines the problems of lateral spread and anisotropy. The old empirical methods used to hot rolling of shapes cannot be used to predict the spread. The single option is to use 3D finite elements with an anisotropic material formulation. As a means of controlling the accuracy of the program, experimental flat rolling can be carried out and the results compared to the FE predictions[10].

2. Theoretical Background

2.1 Width of Contact Area Between the Rolls and Wire

To achieve a relation between the width of contact area, i.e. b value in Fig.1, and the reduction in height of wire, the deformation pattern during flat rolling of wire is considered. The reduction in height of wire, Δh, defined as

$$\Delta h = d_o - h_1 = h_o - h_1 \quad \dots (1)$$

where $d_0(=h_0)$, and h_1 are the initial diameter of wire and the final height of the flattened wire, respectively. In side pressing test of rod, macroscopic shear bands are produced by the formation of two dead metal zones due to the existence of friction between the tools and wire [11]. It has been reported that the shear bands are observed in metallographic cross-section of rods and their morphology follows the reduction in height of rods, as shown in Fig.(2) b and c.

The shear bands are in an X form as shown in the figure. These bands may be considered as the slip line in side pressing test [12]. It has been ascertained that with increasing the reduction in height, the legs of the X rotate away from the primary compression axis[11,13]. From the FEM results presented by Iankov[14] and Pesin et al. [15] for the wire flat rolling process, one may conclude that after flat rolling the wire, there are two bands of X form in cross-section of wire with extremely difference in deformation with respect to the other area. Using the idea of rotation of X legs with increasing the reduction in height of wire, the width of contact area between the wire and rolls in wire flat rolling process can be calculated. Regarding to this point, the b value can be calculated by the following relation in region ABC of Fig.(2) b[16,17]:

$$\frac{b^2}{4} + \frac{h_1^2}{4} = \frac{h_o^2}{4} \quad \ldots \quad (2)$$

$$b = \sqrt{h_o^2 - h_1^2} = \sqrt{\Delta h(h_o + h_1)} \; . \; (3)$$

$$b = \sqrt{\Delta h(2h_o - \Delta h)} \quad \ldots \quad (4)$$

Actually, the length of bands is slightly increased. If it is assumed that the increase is equal to Δh/2, Eq. (4) can be written as:

$$b = \sqrt{2h_o \Delta h} \ldots \; (5)$$

2.2 Lateral Spread of Wire in Wire Flat Rolling

Another important parameter in wire flat rolling process is the lateral spread of the wire. An approach reported for the spread in strip rolling is as follows [18]:

The mean vertical stress between the rolls and strip can be regarded as the normal pressure (*s*), corresponding to a lateral compressive stress of *ms*, where *m* is a function of the geometry of the plastic zone, rolling temperature and composition [6]. The value of *m* lies between that of plane strain and plane stress deformation condition, i.e. $0 \le m \le 1/2$. Neglecting the stress in the longitudinal direction, then from the Levy–Mises plastic stress–strain relations, we get [18]

$$\frac{d\varepsilon_2}{-d\varepsilon_3} = \frac{1-2m}{2-m} = p \quad 0 \le p \le \frac{1}{2} \; \cdots (6)$$

$$\frac{\ln\left(\frac{W_1}{W_o}\right)}{\ln\left(\frac{h_o}{h_1}\right)} = p \quad 0r \quad \frac{W_1}{W_o} = \left(\frac{h_o}{h_1}\right)^p \ldots \; (7)$$

where $d\varepsilon_2$ and $d\varepsilon_3$ are the strains in width and height and W_0, W_1, h_0 and h_1 are the initial width, final width, initial height and final height of strip, respectively.

Using the experimental results, Wusatowski has suggested the following relationship for the spread in strip rolling process [18,19]:

$$\frac{W_1}{W_2} = a'b'c'd'(\frac{h_o}{h_1})^p \quad \cdots \quad (8)$$

where p is a function of the roll diameter and ratio of initial width to height of strip. Also, $a', b', c', and\ d'$ are correction factors, slightly different from unity, which allow for the variation in steel composition, rolling temperature, rolling speed and roll material, respectively [18]. It is interesting to note that Eq.(7) is similar to Eq.(8) derived from the experimental results. The difference between these relationships is due to the existence of stress in the longitudinal direction. To develop spread formula for flat rolling of wire one may modify Eq.(8) by assuming that $W_0 = h_0 = d_0$, where d_0 is the initial diameter of wire. At each deformation condition, h_1, b, and W_1, shown in Fig.(1), were calculated. Thus, using the calculated values, the graphs of W_1/W_0 versus h_0/h_1 were plotted at different roll speeds.

3. Finite Element Modeling

In this research the code DEFORM-3D V6.1 was used to perform finite element analysis of wire flat-rolling process. This software is specifically designed to analyze bulk plastic deformation, and is especially suited for the present analysis. It takes advantage of the fact that plastic deformation is usually highly localized. It assigns rigid elements to the regions of the part that are not deforming, thereby reducing the number of calculations performed at each step of the simulation [20]. It also updates nodal coordinates using a higher order scheme. This special algorithm accurately takes into account the rotation of the object when calculating new location of the rolled part. Details of this code are well established and have been reported elsewhere [21–24].

A 3D finite element rolling model has been constructed to simulate a single pass of the wire flat rolling process, see Fig.(3).High carbon steel wires of 5.5 mm diameter were used as the simulated material in this work. The rolling parameters are shown in Table (1). At each deformation condition the rolling force and geometrical characteristics of the flat wires i.e. h_1, W_1, and b were numerically estimated by the finite element code, see

Figure(4). The rolling reduction in height was defined as $2r_o - h_1$, where r_o and h_1 are the radius of initial wire and the final height of flat wire, respectively.

4. Results and Discussion

To validate the predicted results obtained from the constructed finite element model, it is necessary to compare these results with experimentally measured data. The experimental data of Kazeminzhad and Taheri [1] were chosen to achieve this validation. The validation of the predicted results can be arranged in the following manner.

4.1 Variations of Rolling Force Due to Roll Speed Changes

Fig.(5) shows the effect of rolling speed on the rolling force at different percentage reduction in height. It is clear that increasing the rolling reduction, increases the rolling force. This can be attributed to the increase in redundant work due to large plastic deformation accompanied with high reduction. Moreover in some ranges of rolling speed, the rolling force decrease while in the other ranges it increases. Rowe [25] reported that by increasing the roll speed, the redundant work increases near the surface of the workpiece. Regarding this point, increasing the roll speed can increases the rolling force. Zhang and Lenard [26] noticed that by increasing the roll force, the coefficient of friction between the wire and rolls decreases resulting in reduction of friction work, it is, therefore, concluded that by increasing the roll speed, the rolling force are decreases. Fig.(6) shows the effect of roll speed on the strain rate at constant percentage reduction in height Δh=10.9% at room temperature. It can be seen that increasing the roll speed will increases the strain rate, while roll speed has a negligible effect on the flow stress as the strain rate sensitivity exponent for high carbon steel at room temperature is very small.

4.2 Effect of Reduction in Height on Width of Contact Area

The variations of final width of contact area, b, versus the reduction in height at roll speed ***V***=42.5 rpm are shown in Fig.(7). Δr represents the value of deformation which happens in the radius of wire during rolling and can be calculated using the relation. $\Delta r = \left(2r_o - h_1\right)/2$. Kazeminzhad and Taheri[1] proposed an empirical relationship between *b* and Δr denoted by. $b = 5.64\sqrt{\Delta r}$. The relationship between *b* and, Δr derived from the results of finite element prediction, show that there is a good agreement with empirical relationship. Also it is observed that the b value is proportional to the square root of reduction in height of wire. This result is consistent with the results presented by Pater and Weronski [12,17] for the width of contact area in cross-wedge rolling and rotational compression of rod.

4.3 Lateral Spread of Wire

The graph relating $W_1/W_o \ to \ h_o/h_1$ at a roll speed of 42.5 rpm was shown in Fig.(8). As can be seen from the figure, increasing h_o/h_1, the magnitude of W_1/W_o is increased and the following relationship can be derived

5. Conclusions

1. The finite element method can give a good agreement for the prediction of deformation behavior in wire flat rolling using
2. A negligible increase in flow stress and rolling force does occur due to increase in the strain rate at room temperature.
3. The behavior of rolling force variation versus roll speed depends on the rolling reductions.
4. During the deformation of flat wire rolling, the b value is proportional to the square root of reduction in height of wire.

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Table (1): Rolling Reduction, Speeds, and Rolling Parameters Used in this Study

h_o (mm)	h_1 (mm)	Reduction (%) $(h_o-h_1)/h_o$	Roll speed (rpm)
5.5	4.9005	10.9	42.5, 50, 60, 69.5, 81
5.5	4.4220	19.6	42.5, 50, 60, 69.5, 81
5.5	3.9435	28.3	42.5, 50, 60, 69.5, 81
5.5	3.4815	36.7	42.5, 50, 60, 69.5, 81
5.5	3.0250	45	42.5, 50, 60, 69.5, 81
Roll diameter = 150 mm Roll width = 200 mm Rolling temperature = 20 ºCd			

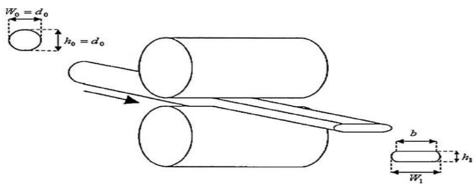


Figure (1): Sketch Showing the Process of Flat Rolling[1]

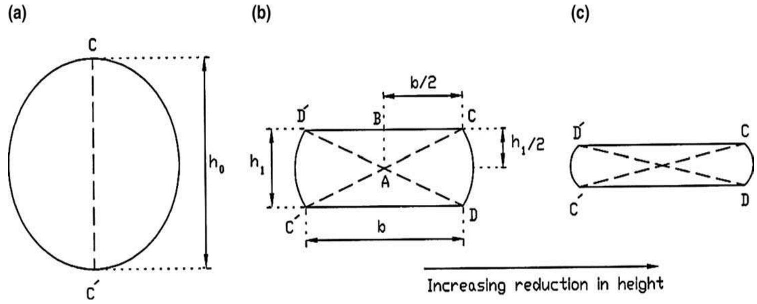
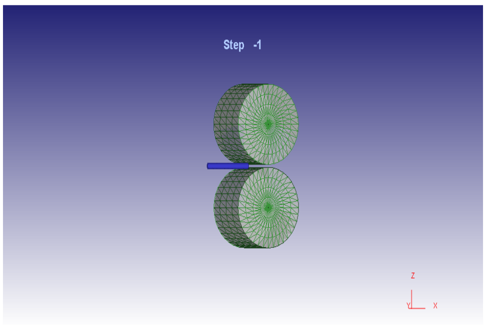


Figure (2):Schematic Illustration of the Effect of Reduction in Height of Wire.[15]



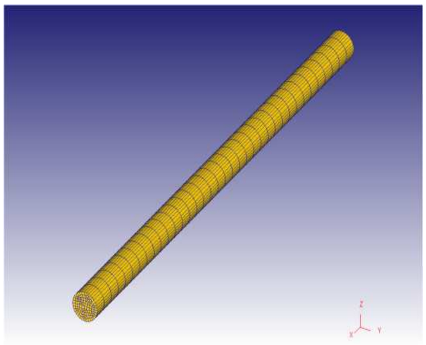
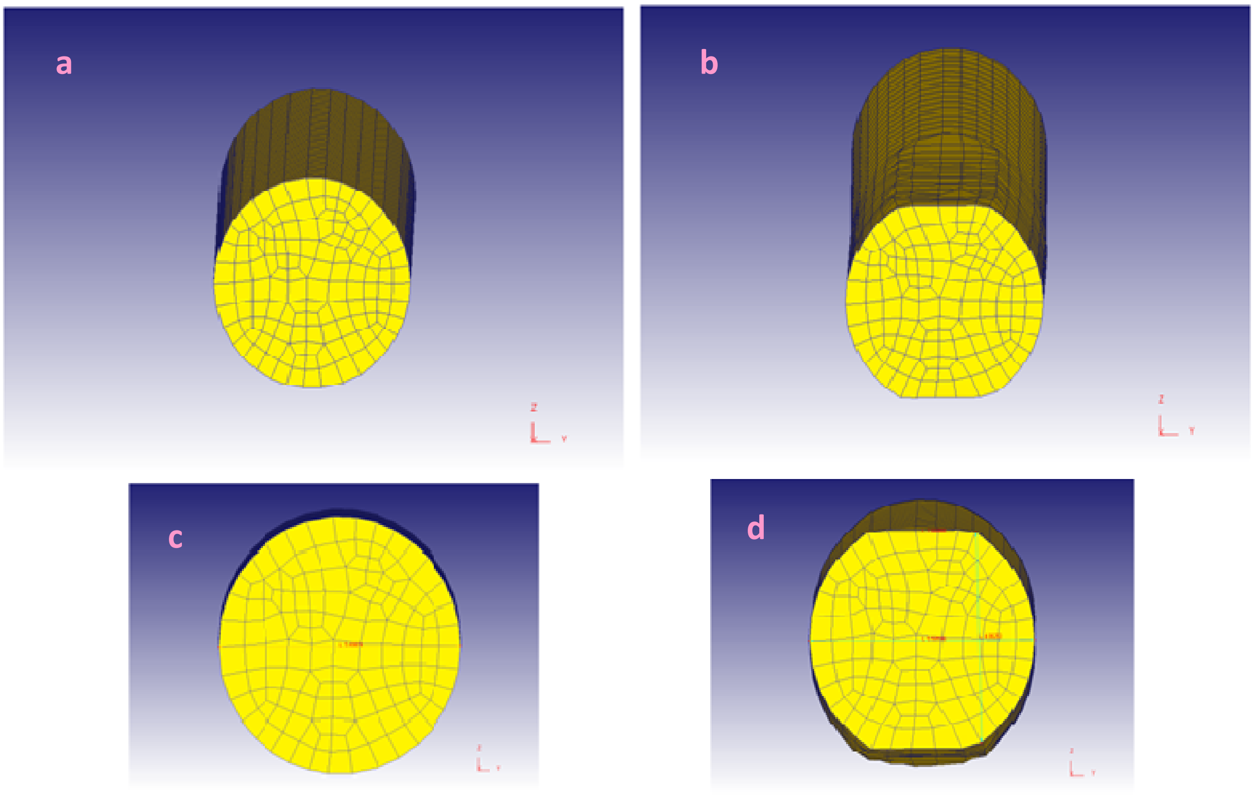


Figure (3): (a) 3D Finite Element Model (b) Meshed Wire



Figure(4) Numerically Measured Geometrical Characteristics of the Flat Wires. h_1, W_1, and b.
a. Wire before Rolling b. Wire after Rolling
c. Geometry before Rolling d. Geometry after Rolling

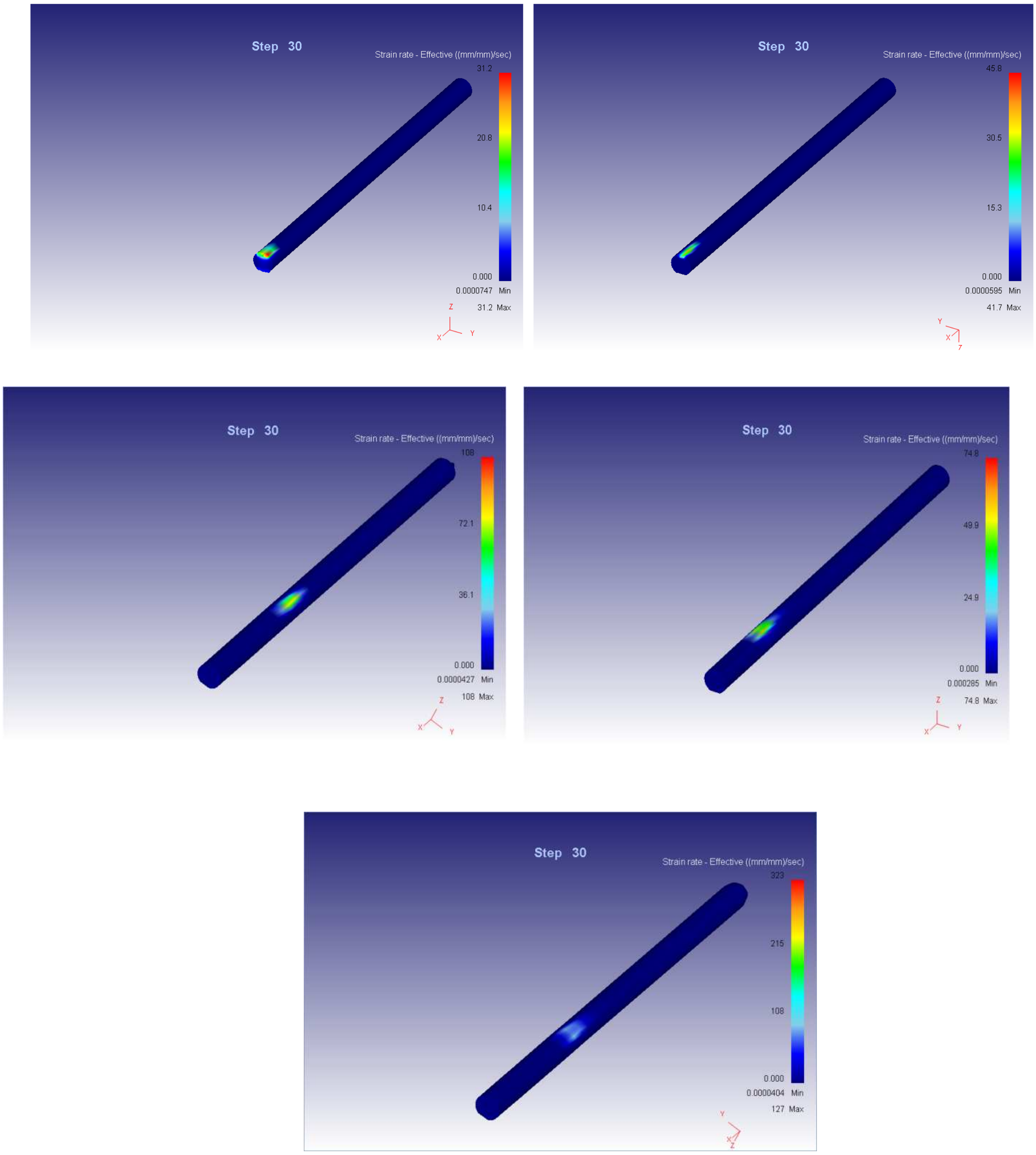


Figure (6) Effect of Roll Speed on the Effective Strain Rate at Δh=10.9%

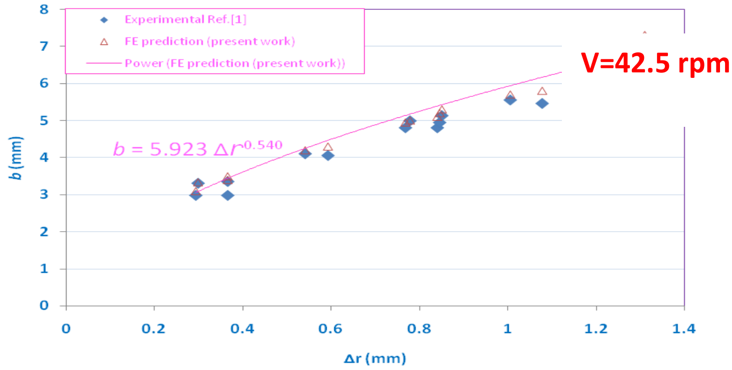


Fig.(7) Dependance of the Width of Contact Area after Rolling on Δr

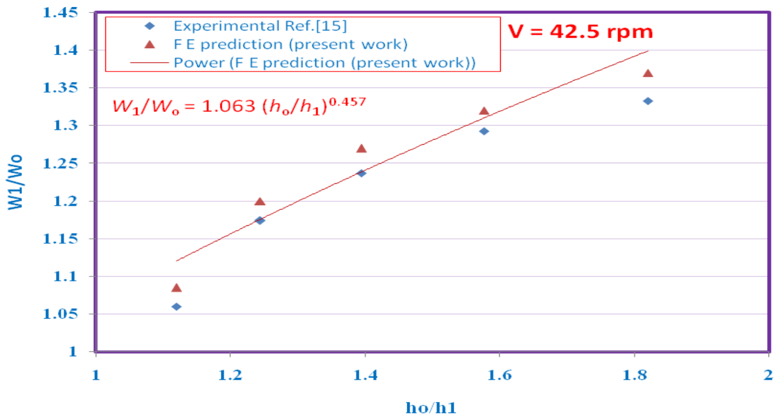


Fig.(8)Dependance of W1/Wo on ho/h1

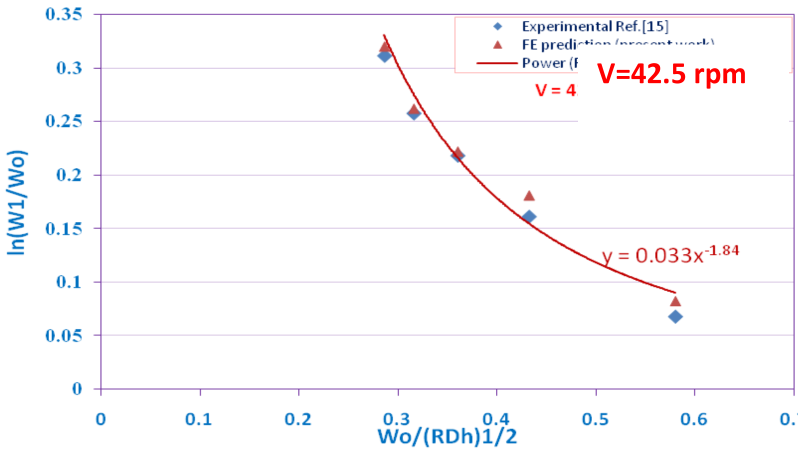


Fig.(9)Dependance of ln(W1/Wo) on Wo/(RDh)1/2