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Določevanje nevtralne točke pri ploskovnem valjanju

Determination of the Neutral Point in Flat Rolling Processes

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Raziskave na področju postopkov valjanja so izrednega pomena, kajti dejstvo je da je bilo veliko število izdelkov med postopkom izdelave vsaj enkrat udeleženo v postopku valjanja. V tem prispevku je analizirano ploskovno valjanje z uporabo analitičnih in metod MKE, z vidika določevanja vpliva zmanjšanja debeline in hitrosti valjanega tračnega jekla ter vpliva tornega količnika na lego nevtralne točke.

Za primerjavo obeh rezultatov modeliranja (analitičnega in MKE) je moč skleniti, da so v dobri sodovisnosti.

V obeh primerih modeliranja je predpostavljeno ravninsko napetostno polje. Na podlagi tega je bila za analizo napetostnega in deformacijskega polja ustvarjena 2-D mreža pri vseh obravnavanih modelih. S takimi modeli je moč določiti premike valjev za različne debeline valjanega tračnega jekla.

Obravnavan proces je štirivaljno oporno valjanje, pri katerem so za analizo mreženi vsi deli z namenom modeliranja napetostnih in deformacijskih polj ter polj pomika in hitrosti.

(Ključne besede: valjanje, modeliranje, metode končnih elementov, SLAB metoda)

Studies of rolling processes are very interesting because a large quantity of produced parts are rolled at some point in their fabrication. In this paper the flat rolling process is analyzed using the FEM and an analytical method in order to determine how the reduction, the velocity of the strip and the frictional coefficient affect the position of the neutral point.

Both the analytical and FEM results are compared and we can say that analytical equations and the FEM modeling are in good agreement.

The plane strain assumption is used in the FEM and in the analytical study, so, in order to study stress and strain, a two-dimensional mesh was considered for all the models. With such models, the deflection of the rolls for different strip thicknesses can be determined.

The studied configuration is a four-high rolling system and the rolls and the strip are meshed in order to obtain their strain, stress, displacements and velocity fields.

(Keywords: rolling, modeling, finite element methods, SLAB method)

0 UVOD

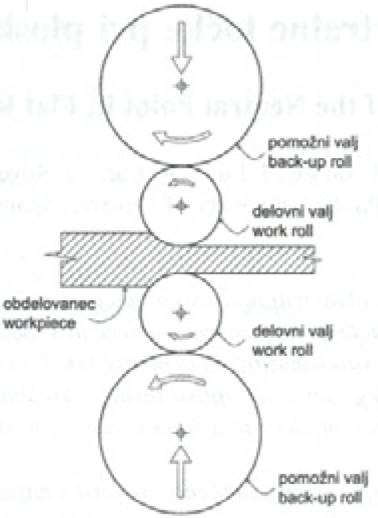
Večina izdelkov na trgu je bila med izdelavo vsaj enkrat vključena v postopek valjanja. Valjanje je postopek plastifikacije materiala, pri katerem se debelina oziroma prerez tračnega jekla zmanjša ali spreminja z uporabo tlačne obremenitve na obdelovanec prek valjev ([1] in [2]). V tem delu je predstavljena primerjava modeliranja postopka z metodo MKE in metodo SLAB ([3] in [4]).

Na sliki 1 je prikazan sistem štirivaljnega opornega valjanja. Tak sistem valjanja je široko

0 INTRODUCTION

Most parts are rolled in at least one of their manufacturing stages. Rolling is a plastic deformation process in which the thickness of a strip or the cross-section of a bar is reduced or changed by applying compressive pressure through a set of rolls ([1] and [2]). In this work, a comparison between a finite element analysis and the SLAB method ([3] and [4]) is presented.

In Figure 1 the four-high rolling configuration is shown. This is a widely used



Sl. 1. *Sistem štirivaljnega opornega valjanja*
Fig. 1. *Four-high rolling mills configuration*

uporabljan, ker so za velika zmanjšanja debeline tračnega jekla potrebne majhne moči. Poleg tega so nadomestni valji ob zamenjavi pri takem sistemu bistveno cenejši od drugih.

Glavni problem pri simuliranju postopkov je popis oz. določitev robnih pogojev sistema. Bolj ko se predpostavljeni robni pogoji ujemajo z dejanskimi, večja je dosežena natančnost simulacijskega modela.

Drugi pomemben vidik, ki mora biti deležen velike pozornosti pri modeliranju, so stiki med posameznimi deli sistema, kar je obravnavano v naslednjem poglavju. Pri simulaciji obravnavanega primera je zaradi geometrijske simetričnosti lahko upoštevana le polovica sistema. To močno zmanjša računski čas brez izgube natančnosti. Ker je dolžina tračnega jekla veliko večja od debeline (1000 mm >> 5 mm), lahko postopek obravnavamo ravninsko, ne da bi pomembno povečali napako modela.

Predmet tega prispevka je določitev položaja nevtralne točke med postopkom valjanja. Izkaže se, da so rezultati, pridobljeni numerično z MKE, primerljivi z rezultati, dobljenimi z metodo SLAB. Za primerjavo

configuration when low power and big reductions are required. Moreover, in this configuration, the rolls are cheaper to replace than in others.

To correctly describe the boundary conditions is one of the most difficult things to do when processes have to be simulated. The more similar the applied boundaries are to those that appear in the real process, the greater the accuracy of the simulation.

Another important aspect to consider is the contact between the different parts of the system. This is discussed in the next section. Only half of the configuration needs to be simulated due to the symmetry of the process. This decreases the calculation time without losing any accuracy. Since the strip's length is much greater than its thickness (1000 mm >> 5 mm) a plain-strain assumption can be employed without any significant loss of precision.

In this paper the location of the neutral point in the rolling processes is studied. The FEM results are compared with those obtained by using the

Preglednica 1. *Simulacije različnih debelin*
Table 1. *Different reductions simulated*

začetna debelina / initial thickness [mm]	5	4,5	4	3,5	3	2,5
končna debelina / final thickness [mm]	2					
zmanjšanje / reduction [%]	60	55,5	50	43	33,3	20

so bila simulirana različna zmanjšanja debeline obdelovanca, kar je prikazano v preglednici 1.

1 ANALIZE MKE IN SLAB

V tem poglavju je predstavljeno modeliranje postopka. Obravnavane izmere valjev so določene na podlagi dejanskega stroja iz industrije [2]. Pomožna oz. oporna valja imata premer 500 mm, medtem ko imata delovna valja premer 200 mm. Začetne in končne debeline tračnega jekla so predstavljene v preglednici 1.

Za modeliranje je najprej potrebno mreženje vseh elementov. Za mreženje sta lahko uporabljeni dve strategiji. Ena od njih je mreženje z majhnimi elementi, pri katerih bodo stiki dobro popisani. Vendar taka metoda močno podaljša računski čas.

Druga možnost je ustvarjanje mreže z večjimi elementi, s tem da se v lokalni okolici stikov, kjer je potrebna večja natančnost, izvede ponovno mreženje z manjšimi elementi ([5] in [6]). Tako je dosežena enaka natančnost ob krajših računskih časih.

V tem prispevku je bila uporabljena slednja metoda, saj obravnava manjše število elementov in tako potrebuje krajše računske čase.

Ponovno mreženje je tu izvedeno le v stičnih območjih, med pomožnim in delovnim valjem ter med delovnim valjem in valjanim tračnim jeklom. Ponovno mreženje v teh območjih je prikazano na sliki 2(a). Pri vseh simulacijah je bilo uporabljeno dvonivojsko ponovno mreženje. S tako metodo je

SLAB method. In addition, different reductions were simulated, as shown in Table 1.

1 FEM AND SLAB ANALYSIS

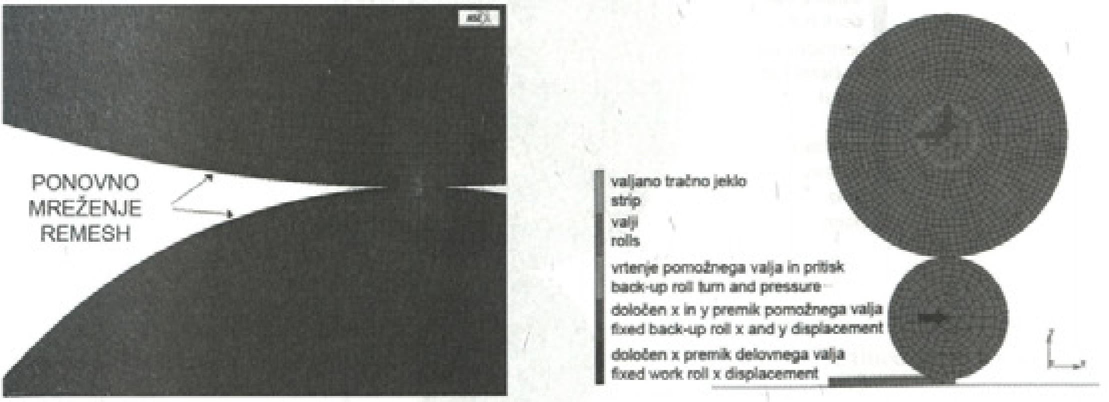
The modeling of the process is presented in this section. The dimensions of the rolls were taken from an actual machine used in industry [2]. The back-up rolls and the work rolls have a diameter of 500 mm and 200 mm, respectively. The initial and final thicknesses of the slabs are presented in Table 1.

Two meshing strategies can be applied to mesh the rolls. Meshing both rolls with a small element, in order to simulate the contacts correctly, is one of them. However, this method will very much increase the computational cost.

Another strategy is to create a mesh with a bigger size of element ([5] and [6]) and introduce a remeshing in the contact zone. This will produce a mesh with a smaller element size in the contact zone, where the precision is needed. This means the same precision, but with a smaller computational cost.

In this paper a second method was employed to reduce the number of elements, which also reduces the time of the calculation.

The remesh is applied to the zone between the back-up rolls and the work rolls and between the work roll and the strip. The remeshing between the rolls during the calculation can be clearly observed in Figure 2 (a). Two levels of remeshing were used in all the simulations. The contact-



(a) Ponovno mreženje v stičnih območjih
(a) Remesh in contact zones

(b) Robni pogoji
(b) Boundary conditions

Sl. 2. *Kriterij ponovnega mreženja in robni pogoji*
Fig. 2.*Remeshing criteria and boundary conditions*

moč dobiti v stičnem območju več vozlišč, kar poveča natančnost določitve stičnega tlaka in gradienta stičnega tlaka.

Za simulacijo postopka valjanja s štirimi valji so potrebni štirje robni pogoji. Prvi je premik valja v smeri *x* (vzporedno osi valjanja), uporabljen v središču delovnega valja. Drugi je pritrditev središča pomožnega valja v obeh smereh (smeri *x* in *y*).

Tretji pogoj je tlak med delovnim in pomožnim valjem, ki neposredno določa potrebno silo za premik delovnega valja. Zadnji robni pogoj je kot zavrtitve pomožnega valja.

Zadnja dva robna pogoja sta določena neposredno iz stikov. Stik med pomožnim valjem in togo gredjo v središču tega valja je deformljiv – tog. V obeh primerih stikov, med tračnim jeklom in delovnim valjem ter med delovnim in pomožnim valjem, sta ta dva obravnavana kot deformljiv – deformljivi stik. Vsi omenjeni robni pogoji so predstavljeni na sliki 2(b).

Z obravnavo zgoraj opisanih stikov se seveda natančnost rezultatov močno poveča, vendar se močno poveča tudi zahtevnost simulacije.

Gibanje pomožnega valja je neposredno povezano s togim stikom (valj – gred). Gibanje je določeno prek gibanja toge gredi, in če je pomožni valj "prilepljen" nanjo, se valj začne gibati, ko se gred obrne.

pressure changes and the contact-pressure gradient can be more accurately described because more nodes exist in the contact zone.

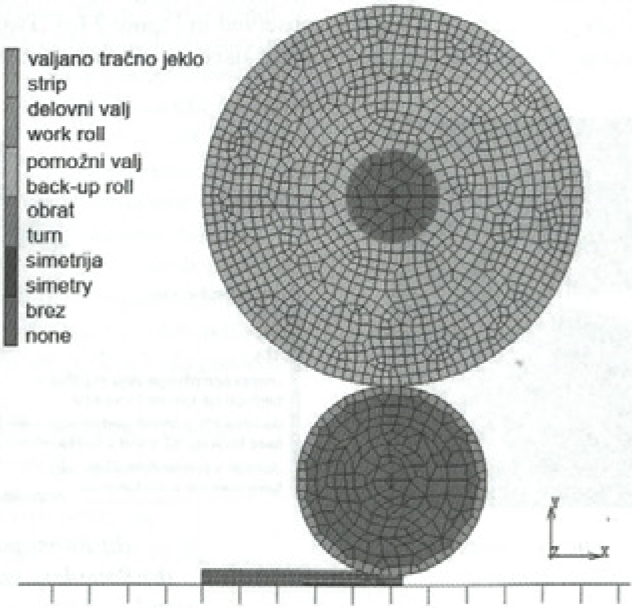
To simulate the four-high rolling process, four boundaries were introduced. The first one is the fixed displacement in the x-axis (parallel to the rolling axis) applied in the center of the work roll back-up roll. Another one is the fixation of the center of the back-up roll in both directions (x-axis and y-axis).

The third condition is the pressure that exists between the back-up roll and the work roll, which introduces the force necessary to move the work roll. The last boundary condition is the turn of the back-up roll.

The last two boundary conditions are introduced by using contacts. The contact between the back-up roll and a rigid circle inside this roll is a deformable-rigid one. Between both the strip and the work roll and between the work roll and the back-up roll a deformable-deformable contact was introduced. These boundary conditions are shown in Figure 2b.

All the above-mentioned contacts increase the accuracy of the solution, but increase significantly the complexities of the simulation.

The motion to the back-up roll is introduced through a contact with a rigid body (a circle). The circle turn is defined through the rigid-body motion option and, as it is glued to the back-up roll, the roll moves as the circle turns.



Sl. 3. *Definicija stikov*
Fig. 3. *Contact definition*

Dodatno je pri simulaciji upoštevana simetrija na podlagi simetričnosti stika togega telesa. Z zamislijo zmanjšanja računskih časov so le zunanji elementi mreže delovnega valja opredeljeni kot stično območje.

Omenjeni stiki so predstavljeni na sliki 3.

Za oba valja je bil izbran linearni elastični model materiala, kjer sta Youngov modul 210 GPa in Poissonov modul 0,3 in predstavljata tipične lastnosti jekla. Za material obdelovanca je bil izbran elasto-plastičen material brez utrjevalnih lastnosti pri deformacijah, in sicer aluminij z Youngovim modulom 70 GPa, Poissonovim modulom 0,3 in zdrsno napetostjo 94,2 MPa.

Tip elementa mreženja v tem prispevku je štirikotnik s popolno integracijo. Po literaturi iz knjižnice elementov MSC ta ponazarja 11. tip elementov [7].

Konvergentna kriterija simulacije sta dva, in sicer pomiki in zaostale napetosti/sile, z namenom določitve bolj natančnih rezultatov. Z izbiro teh dveh konvergentnih kriterijev se sicer računski čas podaljša, vendar se na ta način poveča natančnost rezultatov.

Pomemben dejavnik ostane še velikost časovnih korakov. Le ta je odvisna od več parametrov, to so: velikost elementov mreže, hitrost vrtenja, nelinearnosti: trenje, veliki pomiki in velike deformacije itn.

Rezultati, dobljeni po metodi MKE, so primerjani z analitično metodo SLAB kot primerjavo ([2] in [3]). Nevtralno točko je po metodi SLAB moč izračunati z uporabo enačbe (1) [1]:

Moreover, the condition of symmetry is introduced through the symmetry contact rigid body. In order to decrease the time of the calculation, only the external elements of the work roll were introduced as a contact.

These contacts can be seen in Figure 3.

A linear elastic model was chosen for both rolls with a Young's modulus of 210 GPa and a Poisson's modulus of 0.3 (typical properties for steels). A non-strain hardening elastic-plastic material model was used to simulate the aluminum strip with a Young's modulus of 70 GPa, a Poisson's modulus of 0.3 and a yield stress of 94.2 MPa.

The element type used in this paper is quad for plane strain with full integration, which is number 11 in the element library of MSC [7].

The model is converged in displacement and force residuals in order to ensure accurate results. By using these two convergence criteria, the time of the calculation increases, but a higher accuracy is obtained.

The time step is an important factor to be determined, thus it is greatly influenced by a large number of factors such as element size and rotational velocity, and non-linearities such as friction, large displacements and large deformations, etc.

The results obtained with the FEM are compared with the SLAB analytical method ([2] and [3]). The neutral point can be calculated by the SLAB method using Equation (1) [1]:

$$\frac{h_e}{h_s} = e^{\mu(He-2H)} \quad (1),$$

kjer je μ Columbov torni koeficient in:

where μ is the Coulomb friction coefficient and:

$$He = 2\sqrt{\frac{R}{h_s}}\tan^{-1}\left(\sqrt{\frac{R}{h_e}}\theta_e\right) \quad (2)$$

$$H = 2\sqrt{\frac{R}{h_s}}\tan^{-1}\left(\sqrt{\frac{R}{h}}\theta\right) \quad (3).$$

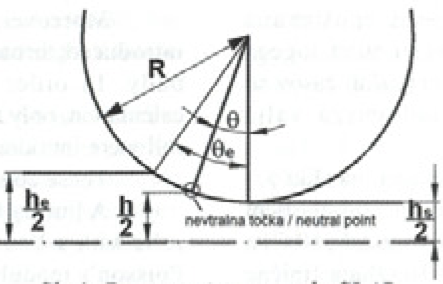
Lego nevtralne točke (h) in kota (θ) je moč določiti s slike 4, kakor določa enačba (4):

The position between the neutral point h and the angle θ can be obtained from Figure 4, as Equation (4) shows:

$$h = h_s + 2R(1-\cos\theta) \quad (4).$$

Z združitvijo enačb (1) do (4), je lega nevtralne točke analitično določena.

Using Equations (1) to (4), the position of the neutral point can be analytically obtained.



Sl. 4. *Parametri za metodo SLAB*

Fig. 4.*Parameters for the SLAB method*

2 REZULTATI

Lega nevtralne točke, kjer pride do spremembe v zmanjšanju debeline obdelovanca, je bila analizirana z različnimi spremembami modeliranja z MKE. Vsi ti rezultati so primerjani z analitično pridobljenimi na podlagi metode SLAB.

Na podlagi enačb (1) do (4) za različna zmanjšanja (pregl. 1), so bile določene lege nevtralne točke (*h*). Rezultati teh enačb so predstavljeni na sliki 6(b).

Določitev nevtralne točke po MKE je mogoča na več načinov. Ena od njih je spremljanje hitrosti vozlišča na tračnem jeklu, ki bo v stiku z valjem, in jo primerjati z hitrostjo valja. Ko sta hitrosti enaki, pomeni vozlišče nevtralno točko. To matematično pomeni določevanje nevtralne točke z iskanjem presečišča hitrosti.

Na sliki 5(a) sta prikazana poteka hitrosti vozlišča in valja v odvisnosti od pomika *x*. Hitrost valja je stalna, in sicer 196,35 mm/s. Ob

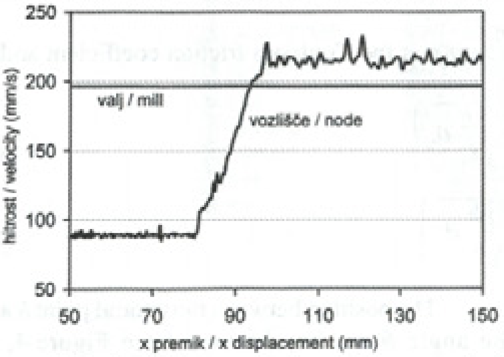
2 RESULTS

From different FEM modelings, the position of the neutral point, when the reduction changes, was obtained. These results were compared with the results obtained using the equations from the SLAB method.

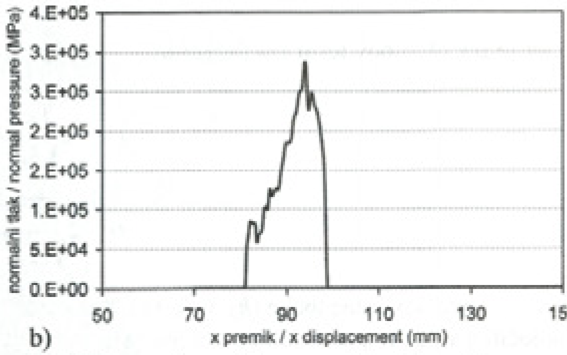
Using Equations (1) to (4), the positions of the neutral point *h* for each reduction of Table 1 were obtained. The curve obtained using these equations can be seen in Figure 6 (b).

There are several ways of obtaining the position of the neutral point in FEM simulations. Plotting the velocity of a node of the strip surface, which will contact the roll, and comparing it with the roll velocity is one of them. When the node velocity equals the roll velocity, the node will be in contact with the neutral point. So in the search for the intersection the neutral-point position is determined.

In Figure 5 (a) the node-velocity plot and the roll velocity versus the *x*-displacement is shown. The roll velocity is constant and equal to 196.35



a)



b)

Sl. 5. *Določitev nevtralne točke na podlagi metode MKE, na oba načina: z analizo hitrosti in pravokotnega tlaka stika.(a – vzdolžni premik proti hitrost vozlišča za primer h_e=5 mm, b – vzdolžni premik proti pravokotni tlak za primer h_e=5 mm)*

Fig. 5. *Determination of the neutral point from the FEM by both analyses of the velocity discontinuity and the contact normal pressure (a – Longitudinal displacement vs. Node velocity for the case of h_e=5 mm, b – Longitudinal displacement vs. Normal pressure for the case of h_e=5 mm)*

vstopu obdelovanca je hitrost vozlišča manjša od hitrosti valja in je večja na izstopu. To pomeni, da bo nekje vmes v vsakem primeru točka, ko bosta obe hitrosti enaki, kar pomeni križanje obeh krivulj in se imenuje nevtralna točka. Določitev in lega nevtralne točke je prikazana na sliki 5 a).

Drug način določitve nevtralne točke je iskanje največjega tlaka na zunanjem vozlišču tračnega jekla med postopkom valjanja. Tak način določevanja je prikazan na sliki 5 b).

Dodatni način določitve nevtralne točke je z analizo torne sile stika v odvisnosti od pomika x, kakor je prikazan na sliki 6 a). Dejstvo je, da trenje nasprotuje relativnemu premiku površin v stiku. To pomeni, ko ima tračno jeklo manjšo hitrost kakor valj, od vhoda do nevtralne točke, oz. večjo, od nevtralne točke do izstopa, se predznak oz. smer torne sile v nevtralni točki zamenjata in sta nična [6].

Na podlagi slik 5 a), 5 b) in 6 a), dobljenih z MKE, je bilo z veliko natančnostjo moč določiti lego nevtralne točke. Razvidno je tudi, da je nevtralna točka vedno na enaki oddaljenosti od začetka na osi x.

Lege nevtralne točke, določene z metodo SLAB ob uporabi enačb (1) do (4) in določene z metodo MKE, so prikazane na sliki 6 b). Očitno je, da imata obe krivulji enak težnjo naraščanja in da je lega nevtralne točke bližje izstopu kakor vstopu.

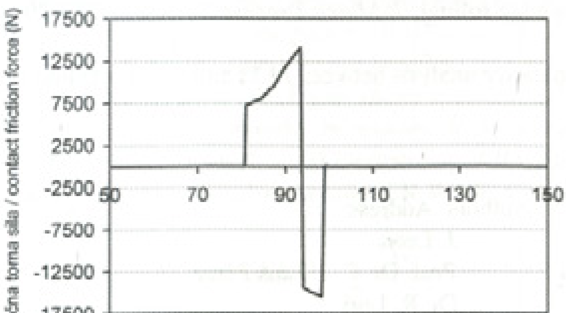
mm/s. The velocity of the node is smaller than the roll velocity at the entrance, but it is higher than the roll velocity at the exit. This means that there will be at least a point were both velocities are equal; that point is the intersection between both curves and it is called the neutral point, which can be clearly determined from Figure 5 a).

Another way to obtain the neutral point is to find the maximum pressure achieved in an external node of the strip while it is being rolled. This pressure evolution can be seen in Figure 5 b).

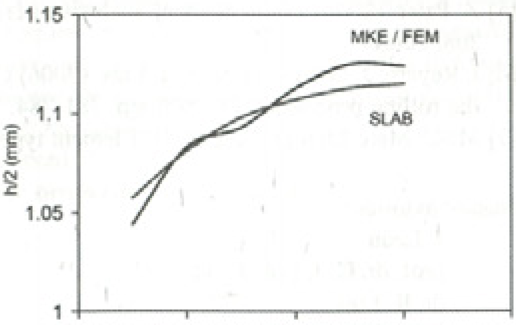
Another way of obtaining the neutral-point position is to plot the contact friction force versus the x-displacement, as Figure 6 a) shows. The friction opposes the relative displacement of the surfaces in contact. This means that, as the strip has less velocity than the roll from the entrance to the neutral point and a higher velocity from the neutral point to the exit, the frictional force will change its sign at the neutral point, where the frictional force is equal to zero [6].

From Figures 5 a), 5 b) and 6 a) high accuracy in the neutral-point location was obtained with the FEM results. It is possible to see from the three figures that the neutral point is located at the same displacement from the beginning of the x-axis.

The position of the neutral point obtained using the SLAB method of Equations 1 to 4 and using FEM modeling is shown in Figure 6 b). As can be seen, both curves have the same tendency and it is clear that the neutral point is closer to the exit than to the entrance.



a)



b)

Sl. 6. *Drug primer določitve nevtralne točke in možnosti primerjave nevtralne točke med analitično in metodo MKE (a – vzdolžni premik proti stična torna sila za primer h_e=5 mm, b – primerjava lege nevtralne točke proti vstopna debelina)*

Fig. 6. *Another way to obtain the neutral point and a comparison of the neutral point for the analytical method and the FEM (a – Longitudinal displacement vs. Contact Frictional Force for the case of h_e=5 mm, b – Comparison of neutral-point location vs. entrance thickness)*

Kljub vsemu je razvidna dobra povezanost med obema metodama (analitično in MKE), čeprav je povezanost boljša pri manjših zmanjšanjih debeline.

Moreover, good agreement between the FEM and the analytical analysis is observed, although the accuracy is greater for small reductions.

3 SKLEPI

V prispevku je predstavljena primerjava modeliranja postopka valjanja z metodama končnih elementov in SLAB. Simulirana so bila različna zmanjšanja debeline tračnega jekla z uporabo štirivaljnega opornega valjanja.

Lega nevtralne točke je bila določena na tri različne načine: Določitev točke, pri kateri se zamenja predznak torne sile stika, analizo spremembe hitrosti in iz vidika pravokotnega tlaka v stiku. Kot končni rezultat določitve nevtralne točke je bilo predstavljeno povprečje vseh treh metod, z namenom določitve natančnih numeričnih rezultatov.

Prikazano je bilo, da se nevtralna točka nahaja blizu izstopa obdelovanca iz postopka valjanja. Poleg tega je bila dokazana dobra soodvisnot med analitično metodo SLAB in numerično MKE.

3 CONCLUSIONS

In this study a comparison between the FEM and the SLAB method was made. Different reductions were simulated, employing a four-high rolling mills configuration.

The neutral-point position for those reductions was determined in three different ways: finding the point where the change in the direction of the contact frictional force occurs, analyzing the change in the velocity, and from the contact normal pressure. The final results were obtained as the mean value of the three ways of measuring the neutral point. This was done with the aim of obtaining good accuracy in the numerical results.

It was shown that the neutral point is close to the exit of the rolling process. Moreover, good agreement exists between the FEM and the SLAB method.

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5 REFERENCES

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