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R. K a z a n d j i e v

Damage Accumulation during Hot Rolling of a Metal Sheet in a Multi - Cell Rolling Mill

The hot rolling of metals is a method of manufacturing products for industry and material for subsequent metal forming. This implies definite requirements on the material characteristics, so that the production be of good quality and appropriate for subsequent plastic deformation. We study the mechanism of damage accumulation during hot sheet rolling in a multi-cell rolling mill - Fig.1.

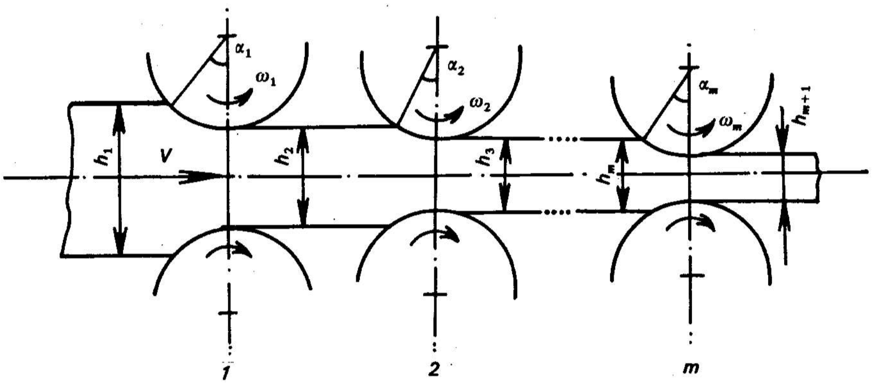


Fig. 1

Following [1], the material damage ψ , acquired during the forming process, is given by

(1)
$$\psi = \sum_{j=1}^{m} \psi_j \, ; \qquad \psi_j = \int_0^{\tau_j} \frac{H(\tau)d\tau}{\Lambda_p(\tau)} \, ,$$

where ψ_j is the damage at each step of the process, H is the shear strain rate intensity and Λ_p is a mechanical characteristics, expressing the degree of shear strain rate attained at the moment of formation of the first macrocracks in the material (m is the cell number, i.e. the number of deformation steps and τ_j is the deformation time at each step of the process). The condition for plastic forming without fracture is $\psi < 1$, and at $\psi = 1$ the first macro cracks appear. We assume that plastic deformation takes place under a constant temperature and steady rolling is considered. We look for ψ for a definite deformation regime. For this purpose the metal stressed and strained state is to be determined, in order to calculate $H(\tau)$, and the characteristic Λ_p is to be found.

a - The shear strain rate intensity H is obtained on the basis of the approach, given in [2]. One-dimensional rolling of a sheet of incompressible material is considered during plain strain. Moreover, we assume that the metal sticks to the roll at a definite point which divides the metal-roll contact area into two sub areas - the metal falls behind the roll in the left sub area and outdistances the roll in the right one. Strain rate intensity ξ_i(and H) is calculated on the basis of the material incompressibility, while stress intensity σ_i - regarding the relation between ξ_i and σ_i

(2)
$$\xi_i = K \sigma_i^n$$

where K and n are material constants, determined by creep experiments performed at the rolling temperature [3], [4].Then

(3)
$$\xi_i = \frac{4\, V_{Bk}\, h_{0k}}{h^2 \sqrt{3}} \operatorname{tg} \varphi \, ,$$

$$\sigma_i = \left[\frac{4\, V_{Bk}\, h_{0k}}{K R^2 \sqrt{3}} \right]^{1/n} \frac{(\operatorname{tg} \varphi)^{1/n}}{\left[\frac{h_{k+1}}{R} + 2(1 - \cos \varphi) \right]^{1/n}} \, ,$$

where V_{Bk} is the roll linear speed in cell $k(k=1 \div m)$, h_{0k} is the "zero" thickness of the sheet during rolling in the k-th cell, k_{k+1} is the sheet thickness, attained after rolling in the k-th cell, φ is the current rolling angle, R is the roll radius ($V_k h_k = V_{Bk} h_{0k} = V_{k+1} h_{k+1}$ is a condition of continuity and h_{0k} corresponds to the metal-roll sticking point).

b - The characteristics Λ_p depends on the coefficient of stressed state $k_1 = \sigma/T$, where σ is the mean normal stress and T is the shear stress intensity. However, $\Lambda_p(k_1)$ is obtained experimentally [1], [2], where the temperature conditions of the real deformation process are to be observed. The dependence $\Lambda_p(\sigma/T)$ is approximated by an exponent

(4)
$$\Lambda_p = A \exp\left(- B\frac{\sigma}{T}\right) ,$$

where A and B are the approximation constants.

It must be noted that the considered criterion for damage accumulation can account for the defect annihilation in the metal by including a heredity function in eqn.(1) - [1]. However, a reliable description of the metal structure changes during hot forming and their effect on the damage occurrence and/or hampering is still needed. The form of the heredity function for slab hot rolling is given in [1], but the problem is to be further developed.

The mean stress σ is calculated according to relations (3) - [3], and the expression for ψ_j at each rolling step is obtained through relations (1) - (4). Then the total material damage ψ can be calculated

(5)
$$\psi = \sum_{j=1}^{m} \left[A \int_0^{\alpha_j} f \exp\left(B\frac{\sigma(\varphi)}{T}\right) d\varphi \right]$$

and f is a function of φ and α_j , determined from rel.(3).

Table 1, h_1 = 0.02 m

Material	Temperature	$K.10^{-37}$	n	$\tau_s.10^7$
Steel	C^0	$(N/m^2)^{-1}.s^{-1}$		N/m^2
9X12	1150^0	6.986	5.151	2.887
R	A	B	Number of cells	
m				
1.03	7.537	0.458	6	

Table 2, h_1 = 0.02 m

Cell number

	1	2	3	4	5	6
Degree of deformation % (not more)	50	45	40	40	25	20
V_B, m/s	1.5	2.3	3.08	4.42	6.17	6.83

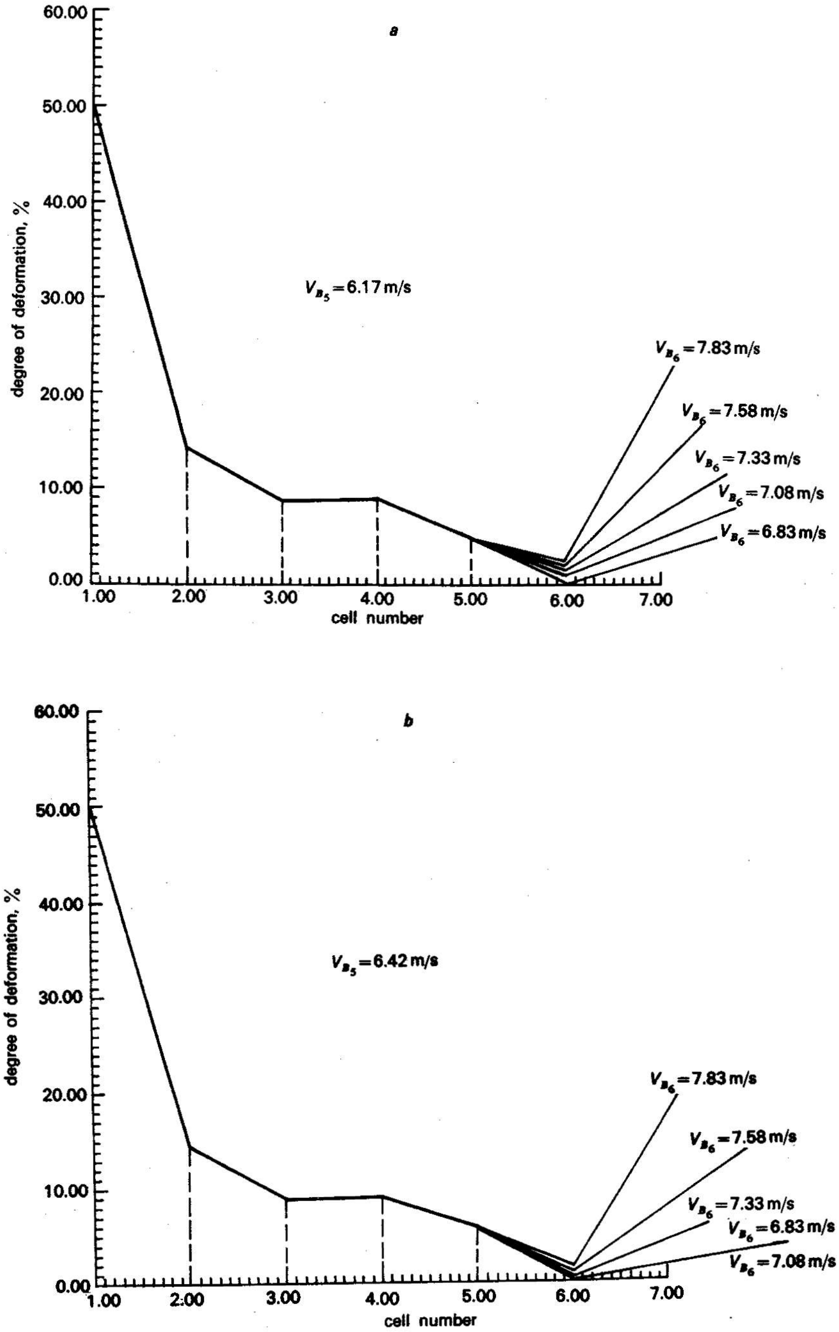

a
60.00
50.00
40.00
30.00
20.00
10.00
0.00
degree of deformation, %
V_{B_5}=6.17 m/s
V_{B_6}=7.83 m/s
V_{B_6}=7.58 m/s
V_{B_6}=7.33 m/s
V_{B_6}=7.08 m/s
V_{B_6}=6.83 m/s
1.00
2.00
3.00
4.00
5.00
6.00
7.00
cell number
b
60.00
50.00
40.00
30.00
20.00
10.00
0.00
degree of deformation, %
V_{B_5}=6.42 m/s
V_{B_6}=7.83 m/s
V_{B_6}=7.58 m/s
V_{B_6}=7.33 m/s
V_{B_6}=6.83 m/s
V_{B_6}=7.08 m/s
1.00
2.00
3.00
4.00
5.00
6.00
7.00
cell number

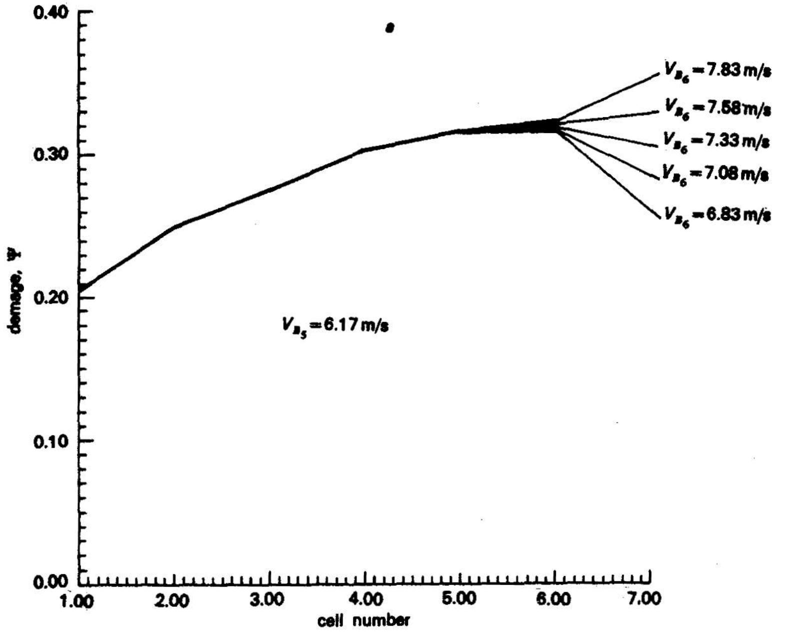
Fig. 2a, 2b

Table 3

	Cell number, V_{B5}=6.17 m/s, h_1 = 0.02 m						
	1	2	3	4	5	6	V_{B6},m/s
Δh,%	50	14.266	8.676	8.852	4.859	.2218	6.83
Δh,%	50	14.266	8.676	8.852	4.859	.8870	7.08
Δh,%	50	14.266	8.676	8.852	4.859	1.4940	7.33
Δh,%	50	14.266	8.676	8.852	4.859	2.0243	7.58
Δh,%	50	14.266	8.676	8.852	4.859	2.5380	7.83
	V_{B5}= 6.42, m/s						
Δh,%	50	14.266	8.676	8.852	5.591	0	6.83
Δh,%	50	14.266	8.676	8.852	5.591	.0002	7.08
Δh,%	50	14.266	8.676	8.852	5.591	.464	7.33
Δh,%	50	14.266	8.676	8.852	5.591	.8315	7.58
Δh,%	50	14.266	8.676	8.852	5.591	1.3510	7.83

Table 4

	Cell number, V_{B5} = 6.17 m/s, h_1 = 0.02 m						
	1	2	3	4	5	6	V_{B6}
ψ	0.2049	0.2493	0.2752	0.3018	0.3160	0.3165	6.83
ψ	0.2049	0.2493	0.2752	0.3018	0.3160	0.3184	7.08
ψ	0.2049	0.2493	0.2752	0.3018	0.3160	0.3199	7.33
ψ	0.2049	0.2493	0.2752	0.3018	0.3160	0.3210	7.58
ψ	0.2049	0.2493	0.2752	0.3018	0.3160	0.3222	7.83
V_{B5} = 6.42 m/s							
ψ	0.2049	0.2493	0.2752	0.3018	0.3182	0.3182	6.83
ψ	0.2049	0.2493	0.2752	0.3018	0.3182	0.3182	7.08
ψ	0.2049	0.2493	0.2752	0.3018	0.3182	0.3195	7.33
ψ	0.2049	0.2493	0.2752	0.3018	0.3182	0.3205	7.58
ψ	0.2049	0.2493	0.2752	0.3018	0.3182	0.3220	7.83


a
0.40
0.30
0.20
0.10
0.00
damage, Ψ
1.00
2.00
3.00
4.00
5.00
6.00
7.00
cell number
V_{B_5}=6.17 m/s
V_{B_6}=7.83 m/s
V_{B_6}=7.58 m/s
V_{B_6}=7.33 m/s
V_{B_6}=7.08 m/s
V_{B_6}=6.83 m/s

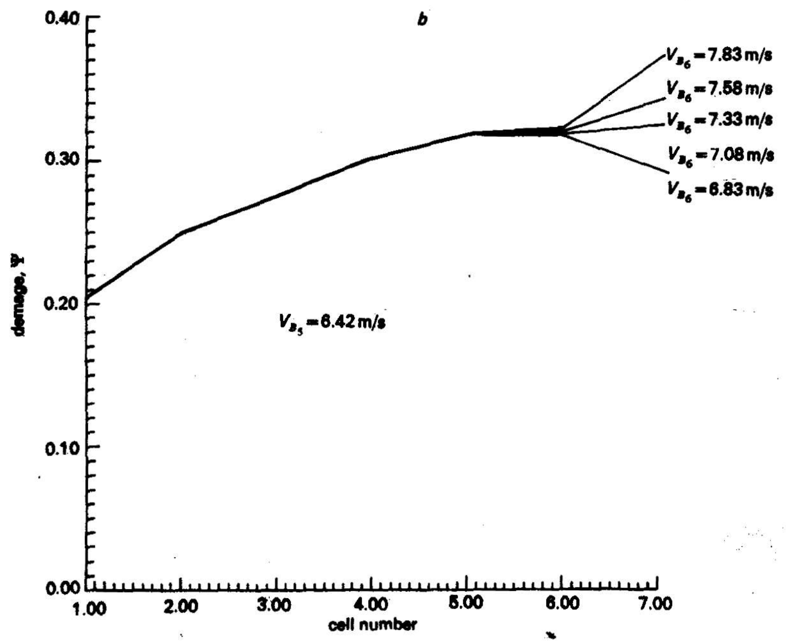

b
0.40
0.30
0.20
0.10
0.00
damage, Ψ
1.00
2.00
3.00
4.00
5.00
6.00
7.00
cell number
V_{B_5}=6.42 m/s
V_{B_6}=7.83 m/s
V_{B_6}=7.58 m/s
V_{B_6}=7.33 m/s
V_{B_6}=7.08 m/s
V_{B_6}=6.83 m/s

Fig. 3 a, 3 b

Since ψ is a monotonically increasing function of α_j (i.e. of τ_j), its minimum value should be obtained for $\Delta h_1=\Delta h_2=\Delta h_3=....=\Delta h_m$ ($\Delta h_k=h_k-h_{k+1}$), i.e. for a uniform distribution of the sheet deformation from cell *1* to cell *m*, but wheather such uniformity is attainable depends on the technologically prescribed rolling regime.

Here we consider an idealization of the real process and we disregard the stages of unsteady rolling - i.e. the start of metal forming and the exit of the ready sheet out of the mill. However, the damage attained in the sheet adges exceeds the critical value and these parts of the sheet are to be removed, since the material quality there is poor.

We analyze as an illustration the hot rolling of a metal sheet in a 6-cell 1700 rolling mill [5]. The type of steel and its mechanical characteristics are given in Table 1, [4], [7], while the work piece dimensions and the technological deformation regime - in Table 2. The degree of deformation in each cell is calculated on the basis of the technological prescriptions. Since it is admissible to increase the linear velocity of the last cells in order to raise the temperature of the ready sheet and thus to compensate the thermal losses, occurring in the sheet during deformation through the previous cells [6], the technological roll velocities in the 5-th and the 6-th cells are varied and the resulting change of the degree of deformation is calculated - Fig.2 *a,b* and Table 3. Material damage ψ in each cell, as well as the entire damage gained during rolling, are calculated as well - Fig.3 *a,b* and Table 4. It is obvious that the accumulated damage grows with the increase of the roll velocity, but it still remains lower than the critical value. This shows that there exist reserves in increasing the mill productivity by minimizing the rolling time.

The present study is a preliminary step to the optimization of a multistage deformation process, whereas metal products with minimum damage are to be manufactured. More than that, the length of the sheet parts where damage is inadmissible could be diminished by an appropriate regulation of the rolling regime. However, a model of deformation closer to reality is to be designed, but, as noted, the physics of the forming process at high temperature is still to be elucidated. Reliable results for the material behaviour at high temperature could be obtained by performing model experiments - e.g. plastic forming of an appropriate model material. Thus satisfactory similarity with the real forming process could be obtained. All this is one of the subjects of the forming process study.

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