EVALUATION OF CYCLIC FLOW CURVES FOR THE CALCULATION OF SHEET METAL FORMING PROCESSES

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Abstract

In order to prove the Bauschinger effect the cyclic flow curves of the materials AlMg3 and C10 have been determined by help of a low-cycle test. The functionality of flow stress and accumulated plastic deformation has been computed for both static and cyclic loading.

Beside the cyclically variform flow stress the notion of the equivalent flow stress to be determined out of the static and cyclic loading characteristics has been introduced.

It can be stated from our measurements that the Bauschinger effect cannot be neglected at the cyclic sheet metal forming processes.

Keywords: flow stress, cyclic loading, Bauschinger effect.

Introduction

For big-size pressed plate spare parts — as automobile body elements, casing of household equipments — it is usual in numerous cases to build in drawbeads to the dies during sheet metal forming. On account of the manifold bending and balancing additional tensile strength is generated in the plate passing through the drawbead (*Fig. 1*) decreasing springback, crimpage, etc. and so improving the conformity of work pieces.

In order to follow the working process by calculation it is necessary to know the power effect developed by the drawbead and necessary to draw the plate (force T in *Fig. 1*). There are several calculating methods known for the calculation of the drawbead force. In the Weideman process [1, 2] the tensile stress in the plate passed through the drawbead — called further on reaction — is composed of the friction on the flat plates, of the rope friction of the plate pulled over the tool elements with different radii as well as of the bending and straightening of the plate. This method does not

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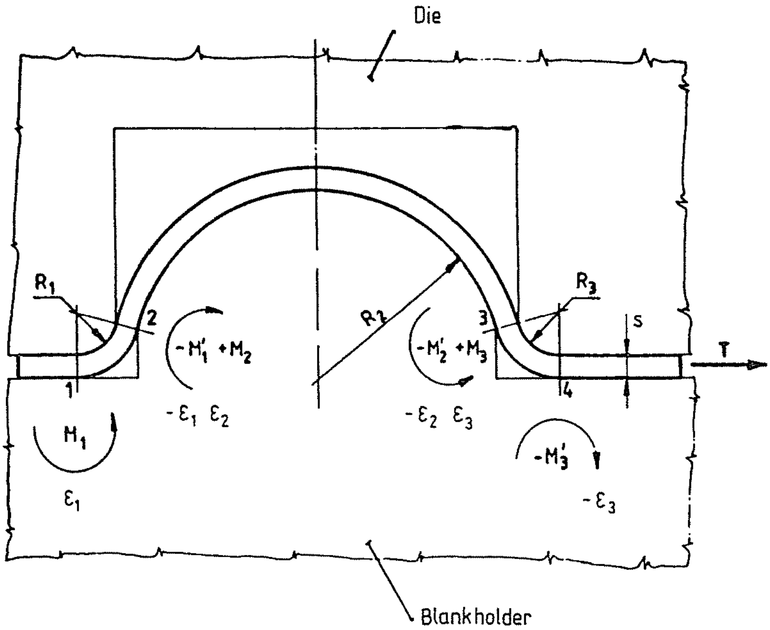

Fig. 1. Load of the plate passed over the drawbead during stretch bending

take in consideration neither the hardness increasing during the process, nor the Bauschinger effect at cyclic bending.

YELLUP [3] was handling the plate sliding over the drawbead as the compound of elementary fibers. NINE [4] carried out an experimental equipment, by which the power necessary to the sliding over the plate band can be separated into the force to multifold bending and straightening of the plate and into the force to overcome the friction. He found that the working process cannot be described by the monotonic stress-strain relation, truth can be described only by the cyclic stress-strain curves, but they did not publish any solution for it.

SUNAGA and MAKINOUCHI [5] elaborated a finite element process for the examination of the drawbead effect. BREKELMANS and HOOGENBOOM [6] analysed the process of plate bending and straightening by applying the upper bound method, without the Bauschinger effect.

The hardening process of the plate slid over the drawbead can be described exactly only in the knowledge of the cyclic flow curve, for the evaluation of which an up-to-date material testing method is necessary.

Upon ground of literature sources [7 – 11] the flow stress (k_f) can decrease during the forming process — depending on the size of cyclic deformation — even by the 40 – 60% of the value of flow stress belonging to monotonic deformation.

In order to clarify the above mentioned phenomena we have carried out experiments to evaluate the flow curve belonging to the cyclic yield load. The shape and the numeric values of the cyclic yield curve are influenced by the measure of elongation by cycles. Determining the average deformation of the plate passed over the drawbead ($\overline{\varepsilon}$) according to [12], it is, in conformity with the markings in *Fig. 1* in case of the drawbead $R_1 = R_3 = 3$ mm and $R_2 = 4$ mm size as well as of an $s = 0.8$ mm thick plate of $\overline{\varepsilon} = 0.053$ value. That is why we have carried out our examinations with an amplitude of strain $\overline{\varepsilon} = 0.05$ resp. $\overline{\varepsilon} = 0.1$

Evaluation of the Cyclic Flow Curve

The shape of the specimen can be seen in *Fig. 2*. The specimens consist of the following materials: aluminium alloy containing appr. 3% Mg (AlMg3) (Hungarian Standard 3714/2–74) and plain carbon steel containing 0.1% C (C10) (Hungarian Standard 31–85). A 250 kN electrohydraulic tensile test machine (type MTS 810) has been used and for the evaluation of the measurements the TestLink system was used in small cycle fatigue test working system [13]. The elongation of the specimens has been computed of a diameter alteration measurement. During the experiments the diameter alteration has been measured by means of an MTS extensometer having a measuring limit of $\Delta d = \pm 2$ mm and a display accuracy to 5 decimal figures. The loading control has been carried out with real elongations at values similar to the deformation generated on the drawbead, i. e. $\overline{\varepsilon} = 0.05$ resp. $\overline{\varepsilon} = 0.1$. During the one cycle the stress-strain values have been fixed in 100 points. The cyclic loading was being continued with frequency $f = 0.1$ Hz until the breaking of the specimen. Parallel with these examinations (test) the static flow curves of materials have been measured also with the Watts-Ford method.

For the actual task the theory of MOSKVITIN V. V [14] elaborated for the case of cyclic elasto-plastic loadings has been applied. Let us mark the elements of the tension and the deformation tensor in the n-th loading cycle by $\sigma_{ij}^{(n)}$, $\varepsilon_{ij}^{(n)}$. Introducing the following differences:

$$\begin{aligned} \overline{\sigma}_{ij}^{(n)} &= (-1)^{(n)} \left(\sigma_{ij}^{(n-1)} - \sigma_{ij}^{(n)}\right) , \\ \overline{\varepsilon}_{ij}^{(n)} &= (-1)^{(n)} \left(\varepsilon_{ij}^{(n-1)} - \varepsilon_{ij}^{(n)}\right) , \end{aligned} \tag{1}$$

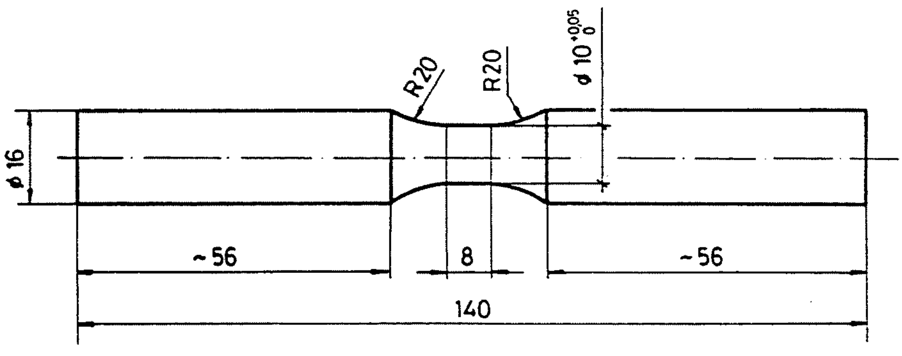

Fig. 2. Sketch of the specimen used for the cyclic test

the relation between the tensions and the deformations in the n-th cycle is according to the above theory:

$$\overline{\sigma}_{ij}^{(n)} - \delta_{ij}\overline{\sigma}^{(n)} = \frac{2\overline{\sigma}_u^{(n)}}{3\overline{\varepsilon}_u^{(n)}} \left(\overline{\varepsilon}_{ij}^{(n)} - \delta_{ij}\overline{\varepsilon}^{(n)}\right) , \tag{2}$$

$$\overline{\sigma}^{(n)} = 3K\overline{\varepsilon}^{(n)} , \tag{3}$$

where $\overline{\sigma}_{ij}^{(n)}$ is standing for equivalent stress alterating by cycles (*Fig. 3*), K for the volumetric elasticity modulus.

$$\begin{gathered} 3\overline{\sigma}^{(n)} = \overline{\sigma}_{kk}^{(n)} , \qquad 3\overline{\varepsilon}^{(n)} = \overline{\varepsilon}_{kk}^{(n)} , \\ \overline{\sigma}_u^{(n)} = \sqrt{\frac{3}{2}\overline{S}_{ij}^{(n)}\overline{S}_{ij}^{(n)}} , \qquad \overline{S}_{ij}^{(n)} = \overline{\sigma}_{ij}^{(n)} - \delta_{ij}\overline{\sigma}^{(n)} , \\ \overline{\varepsilon}_u^{(n)} = \sqrt{\frac{2}{3}\overline{e}_{ij}^{(n)}\overline{e}_{ij}^{(n)}} , \qquad \overline{e}_{ij}^{(n)} = \overline{\varepsilon}_{ij}^{(n)} - \delta_{ij}\overline{\varepsilon}^{(n)} . \end{gathered} \tag{4}$$

After having processed our measurement results, the cyclic flow curve has been approached in the following form:

$$\begin{gathered} \overline{\sigma}_u^{(n)} = E\overline{\varepsilon}_u^{(n)} , \qquad \overline{\varepsilon}_u^{(n)} \leq \frac{c_1(n)}{E} , \\ \overline{\sigma}_u^{(n)} = c_1(n) + c_2(n)\left(\overline{\varepsilon}_u^{(n)} - \frac{c_1(n)}{E}\right)^{c_3(n)} , \qquad \overline{\varepsilon}_u^{(n)} > \frac{c_1(n)}{E} , \end{gathered} \tag{5}$$

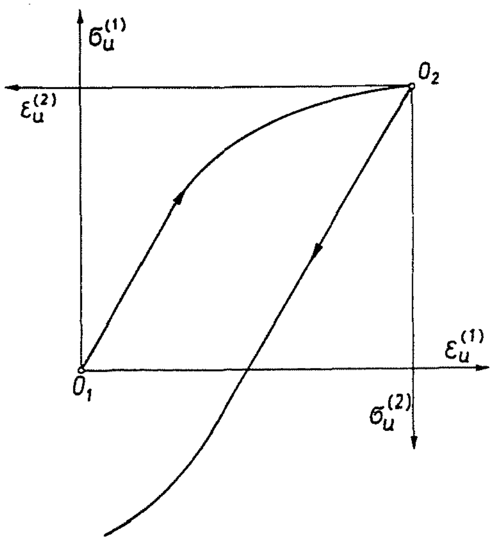

Fig. 3. Sketch of the cyclic flow curve

where E is standing for the Young's modulus (AlMg3: $E = 70000\,\mathrm{MPa}$, C10: $E = 216000\,\mathrm{MPa}$) $c_1(n)$, $c_2(n)$, $c_3(n)$ are parameters in function of the cycle number, determined by function adaptation to the measurement results (*Tables 1 – 4*). The R_{err} values figuring in one of the table columns remind to the truth of the function adaptation [15]

$$R_{\mathrm{err}} = \frac{\sqrt{s^2}}{\sqrt{\sum_{i=1}^{N} f_i^2}} \tag{6}$$

in which $s^2 = \sum_{i=1}^{N} (f_i^* - f_i)^2$ standard deviation between the N-fold f_i value measuring point and — with *Eq.* (5) — the function f_i^* determined at the same abscissa.

In order to prove the Bauschinger effect, we reckoned out of the flow curves determined by compression and tension test also the functionality $k_f - \bar{\varepsilon}_p$ (flow stress, accumulated plastic deformation). The results relating to the different materials and deformation amplitudes are shown in *Figs. 4 – 7*. Beside the cyclically variating flow stress we have defined also a series of monotonic curves derivated from the static and cyclic loading characteristics, which we call equivalent flow stress.

$$k_{f_{\mathrm{eq}}} = \beta k_{f_{\mathrm{stat}}}. \tag{7}$$

Table 1
Parameters of the cyclic flow curve
(material: AlMg3, amplitude of strain $\bar{\varepsilon} = 0.05$)

	AlMg3		strain = ± 0.05	
N°	c_1 MPa	c_2 MPa	c_3	R_{err} %
1	52.7	349.3	0.37	3.67
2	140.1	318.4	0.14	2.73
3	200.3	314.0	0.12	2.91
4	252.1	253.3	0.08	3.23
5	293.8	230.3	0.11	2.73
6	392.3	115.4	0.10	3.45
7	365.6	181.1	0.15	3.50
8	415.7	118.6	0.13	4.89
9	387.5	168.2	0.15	3.60
10	374.9	160.1	0.07	3.27
11	397.3	174.7	0.17	3.89
12	448.5	95.3	0.12	4.21
13	388.1	188.0	0.14	4.21
14	424.4	128.0	0.10	3.17
15	441.0	147.7	0.21	4.13
16	449.7	105.0	0.11	3.91
17	388.9	201.3	0.14	3.61
18	445.5	121.5	0.12	4.58

Parameter β is being computed by utilization of the specific works determined under cyclic and static conditions upon base of the following equation:

$$\beta(\bar{\varepsilon}_p) = \frac{\int_0^{\bar{\varepsilon}_p} k_{f_{\mathrm{cycl}}} \mathrm{d}\varepsilon}{\int_0^{\bar{\varepsilon}_p} k_{f_{\mathrm{stat}}} \mathrm{d}\varepsilon} = \frac{W_{\mathrm{cycl}}}{W_{\mathrm{stat}}}. \tag{8}$$

In *Fig. 8* the variation of parameter β is shown at several cycles of examined loading process. By help of our measurements we presented that there is a considerable difference between the flow stress of the material determined by way of monotonic loading and the flow stress existing at a cyclic deformation. That is why the influence of the Bauschinger effect cannot be neglected while modelling such processes.

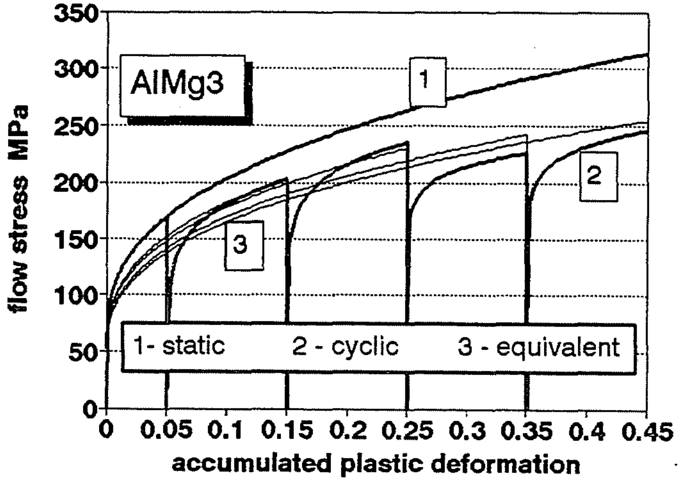

Fig. 4. Variation of the static, cyclic and equivalent flow stress in function of the accumulated plastic deformation (material: AlMg3, amplitude of strain $\bar{\varepsilon} = 0.05$)

Table 2
Parameters of the cyclic flow curve (material: AlMg3, amplitude of strain $\bar{\varepsilon} = 0.1$)

AlMg3		strain = ±0.1		
N°	c_1 MPa	c_2 MPa	c_3	R_{err} %
1	52.7	349.3	0.37	3.67
2	201.5	269.5	0.09	2.51
3	273.4	256.2	0.10	2.20
4	427.4	95.8	0.04	3.55
5	395.4	174.7	0.15	2.88
6	481.3	74.2	0.10	2.90
7	443.8	148.0	0.19	2.61
8	435.0	129.9	0.03	2.98
9	421.1	186.8	0.15	3.07
10	554.7	22.0	0.07	3.17
11	455.9	162.9	0.17	2.96
12	441.6	152.6	0.03	3.71
13	422.8	203.9	0.14	2.54
14	540.7	68.9	0.12	3.91
15	481.9	158.8	0.22	2.20
16	468.9	135.1	0.03	3.02
17	433.8	206.9	0.14	2.82
18	518.4	94.0	0.08	3.66

Table 3
Parameters of the cyclic flow curve
(material: C10, amplitude of strain $\bar{\varepsilon} = 0.05$)

	C10	strain = ±0.05		
N°	c_1 MPa	c_2 MPa	c_3	R_{err} %
1	215.4	855.1	0.23	1.71
2	294.8	1240.6	0.09	6.46
3	297.2	1256.4	0.07	5.66
4	301.6	1277.8	0.07	6.54
5	301.6	1282.3	0.08	7.08
6	307.3	1292.8	0.09	7.91
7	312.7	1286.9	0.07	5.92
8	310.6	1235.6	0.05	4.95
9	293.5	1320.1	0.08	6.91
10	292.9	1332.8	0.08	7.44
11	297.8	1303.9	0.07	5.86
12	298.8	1320.5	0.07	6.23
13	298.9	1347.7	0.08	6.68
14	305.7	1368.4	0.08	7.17
15	300.2	1326.2	0.07	5.60
16	300.9	1336.1	0.07	6.11
17	296.7	1371.0	0.08	6.63
18	297.7	1383.3	0.08	6.98

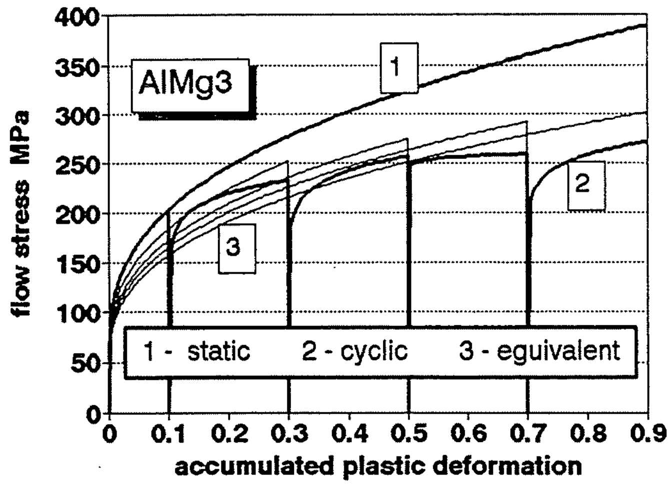

Fig. 5. Variation of the static, cyclic and equivalent flow stress in function of the accumulated plastic deformation (material: AlMg3, amplitude of strain $\bar{\varepsilon} = 0.1$)

Table 4
Parameters of the cyclic flow curve
(material: C10, amplitude of strain $\bar{\varepsilon} = 0.1$)

	C10	strain = ±0.1		
N°	c_1 MPa	c_2 MPa	c_3	R_{err} %
1	215.4	855.1	0.23	1.71
2	408.7	1157.6	0.09	3.55
3	413.2	1177.8	0.06	4.75
4	418.8	1188.2	0.07	4.44
5	414.9	1218.8	0.08	4.66
6	420.4	1174.6	0.06	5.18
7	422.3	1189.1	0.06	5.23
8	422.5	1195.9	0.07	4.47
9	426.6	1232.4	0.08	5.26
10	422.5	1245.4	0.08	5.61
11	420.2	1195.8	0.07	4.52
12	424.1	1204.1	0.07	4.48
13	424.4	1231.9	0.08	5.35
14	428.6	1252.8	0.08	5.31
15	427.0	1202.2	0.07	5.42
16	432.8	1211.8	0.07	4.49
17	440.6	1241.9	0.08	5.34
18	441.7	1191.8	0.06	4.23

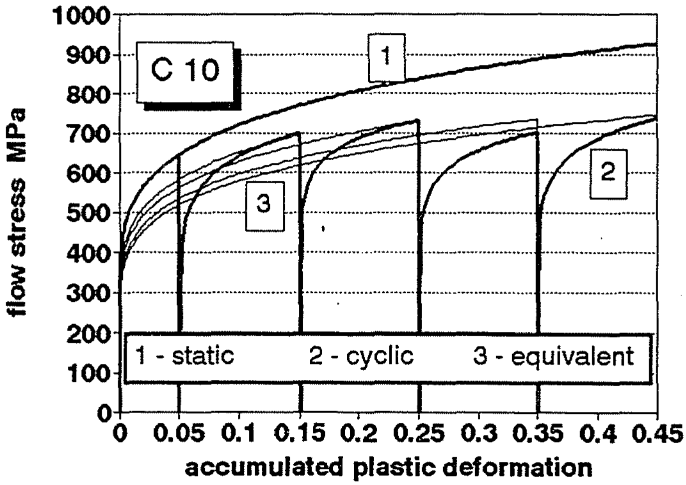

Fig. 6. Variation of the static, cyclic and equivalent flow stress in function of the accumulated plastic deformation (material: C10, amplitude of strain $\bar{\varepsilon} = 0.05$)

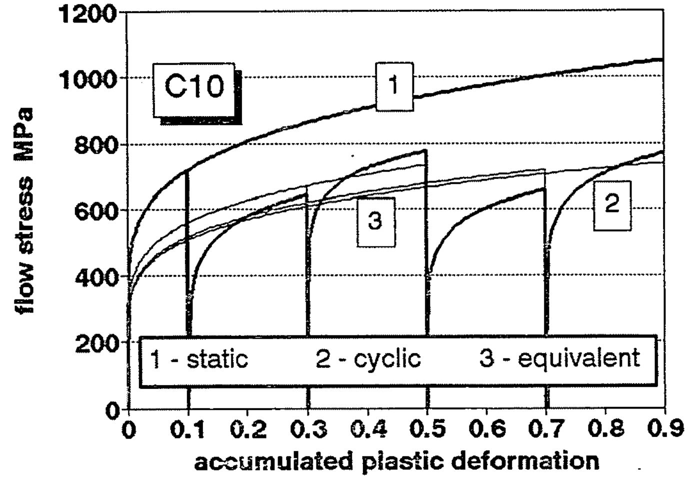

Fig. 7. Variation of the static, cyclic and equivalent flow stress in function of the accumulated plastic deformation (material: C10, amplitude of strain $\bar{\varepsilon} = 0.1$)

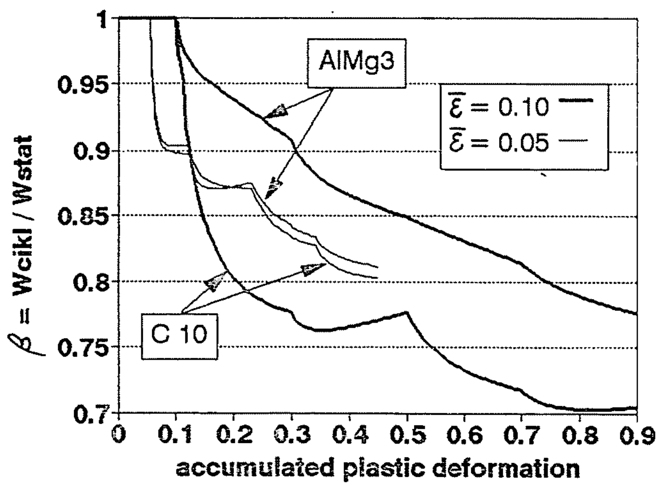

Fig. 8. Variation of parameter β in function of the accumulated plastic deformation for materials AlMg3 and C10, for amplitudes $\bar{\varepsilon} = 0.05$ and $\bar{\varepsilon} = 0.1$)

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