THERMO-MECHANICAL TREATMENT OF LOW-ALLOY STEELS IN HERF MACHINE

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1. Introduction

Physical analysis of factors affecting the transformation of meta-stable austenite has demonstrated that isothermal metal forming by uniaxial tension accelerates the transformation process [1]. Low-temperature tempering of the martensite obtained by rapid cooling of meta-stable austenite formed in the above conditions yields high-tensile steels of sufficient ductility, even if these are low-alloy ones [2]. Accordingly, among the first technical applications, wire drawing has been tested, and has proved an important increase of strength and ductility as compared to patenting, otherwise a rather efficient method of strength increase.

For most of the metal forming technologies, at an arbitrary point of the specimen, the spherical stress tensor describing the stress state is a negative one, as against the spherical tensor of the stress state of the uniformly tensioned test piece. Spherical tensor is one of the physical-chemical condition coefficients, hence obviously, the effects of uniform tension applied in a physical test on either the transformation mechanism or the strength of the developed new structure, has to differ from that in a real forming technology, even if all parameters are equal, including also the value and the rate of deformation.

The effect of spherical stress tensor could be analysed in three extreme cases: hydrostatic tension, compression, and pure torsion with zero spherical stress tensor. From the technological aspect, the hydrostatic compression (negative spherical tensor) is of importance.

Transformation of meta-stable austenite into martensite involves volumetric increase, thus, theoretically, according to the Clausius-Clapeyron equation, the phase change would be counteracted by the hydrostatic pressure. LYUBOV and ZYGARENKO [4] have examined both theoretically and experimentally the effect of hydrostatic pressure in the upper range of the meta-stable austenite field, taking the kind of transformed phases and the diffusion rate into consideration. Hydrostatic pressure was found to inhibit $\gamma-\alpha$

transformation, to shift the TTT diagram to the right, and to accelerate $\alpha-\gamma$ transformation.

Similar phenomena were observed by OSINA [5] upon applying high-rate (50 to 190 m/sec) impact producing no deformation on a specimen in a closed die, where the pressure wave subsisting for about 0.1 m/sec delayed the $\gamma-\alpha$ transformation.

In conformity with the above, metal forming technologies with important hydrostatic pressure components within the stress tensor are expected to be suitable for the thermo-mechanical forming even of steels with short incubation time when mechanical tensile tests would show an immediate transformation of austenite.

Hydrostatic pressure components of the stress tensor are prevalent in rod extrusion among metallurgical forming technologies, as well as in drop forging and in cold and semi-warm extrusion among metal-working manufacturing methods. The work piece is exposed to practically pure hydrostatic pressure at the beginning of extrusion and bar extrusion, as well as at the end of drop forging. Evidently, in the latter case, benefits offered by this effect cannot be made use of.

Hence, theoretically, extrusion forming is a more suitable method. According to the extrusion tests of BLANTER et al. [6], low and high temperature thermo-mechanical forming (LTMT and HTMT) may simultaneously improve plasticity and strength. On the other hand, recently, LIEBIG [7, 8] has demonstrated austenite transformation to accelerate after the static extrusion of overcooled austenite. Again, static extrusion has been applied by PIMENOV [9] and ATROSHENKO et al. [10]. The former applied a tool inconvenient to production, designed solely for thermo-mechanical tests, while the latter has presented work pieces extruded from cylindrical and annular billets of relatively low-carbon, high-alloy steels to warrant high-grade mechanical characteristics.

Relative stability of meta-stable austenite may be improved by higher deformation rates in some cases. No directly relevant data are available but this conclusion has been drawn by MITCHEV et al. [11] from analysing the austenite residues of an impacted high-speed steel. By increasing the deformation rate, the processes become adiabatic, in the case of high deformation a great amount of deformation energy is transformed into heat. Therefore some researchers consider it rather harmful to increase the rate, especially in extrusion [6, 12], while others consider it as a means to increase the strength [2], and even propose it for LTMT, to accelerate the transformation resulting in bainite [13]. HARVEY [14] has named "Blastform" process the high-rate formation of metastable austenite with subsequent quenching. He has quoted as a principal advantage that dies and punches can sustain much higher short-time loads in "shock condition" than in quasi-static loading condition.

ATROSHENKO et al. [10] stated that in thermo-mechanical processes the extrusion tool and the machine are exposed to 1.7 $\sim$ 2.3 times the load in normal hot or semihot technologies.

These promising findings induced us to produce high-strength machine parts from low-cost, low-alloy raw material by thermo-mechanical extrusion. The parameters of the process had to be such as to clearly answer the arisen contradictions, viz.:

1. Is there a thermo-mechanical effect acting in thermo-mechanical forming by extrusion under adiabatic conditions, and if there is, does it improve the mechanical properties?

2. What is the load of the tool in high-speed forming, and what is the most convenient tool construction?

3. What are the quality characteristics of the products possible by this method?

To answer question 1, it was assumed as work hypothesis that no strength increase accompanied by other than slight ductility loss can be accepted. To check this item, in addition to the normal strength characteristics, absorbed energy to fracture has been determined according to the earlier deduced formula [15]:

$$W_c = 0.9\,\sigma_B \frac{\psi_c}{1-\psi_c} \left[\frac{\text{mkgf}}{\text{cm}^3}\right] \tag{1}$$

where σ_B = ultimate tensile strength (kgf/mm^2) and ψ_c = reduction of area. Accordingly, thermo-mechanical forming is accepted as efficient if the energy to fracture of the product is equal to or greater than the maximum energy achieved by conventional thermal treatments.

2. Technological tests

Test material has been selected first so as to be covered by many comparative data on conventional thermo-mechanical formability and second, to be a relatively low-alloy steel. NCM 15 according to the Hungarian Standard MSz 69-60 seemed to fulfil these requirements; its counterparts being the *American* steel 4340, the *British* En 24 and the *Soviet* 35XHMA and 40XHMA grades. Chemical composition of the tested steel is shown in Table I:

Table I

C%	Mn%	Si%	P%	S%	Cr%	Ni%	Mo%
0.31	0.73	0.30	0.013	0.011	1.57	1.56	0.27

Geometry of the specimen corresponded to a M 24 ×80 mm socket head shoulder screw (Fig. 1). The billet had been chosen so that deformation of extruded shaft and upset head should be about the same, at the same time the billet should exhibit no deflection during forming (Fig. 2). Extrusion tests took place in a pneumo-mechanical HERF machine type NEK-8, earlier presented by

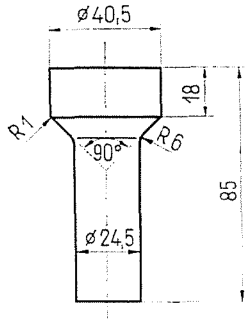


Fig. 1

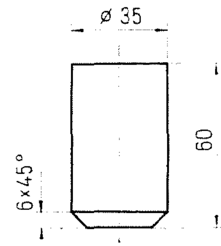


Fig. 2

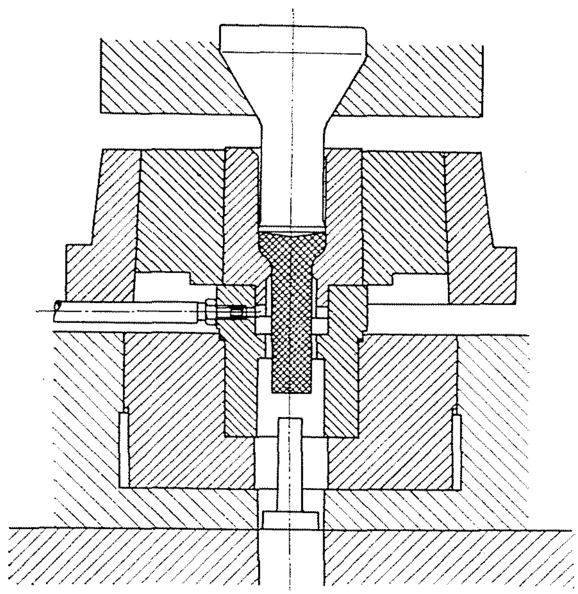


Fig. 3

GILLEMOT et al. [16]. Fig. 3 gives a drawing of the extrusion tool designed specially for the machine.

In conformity with preliminary test data, work pieces have been austenized for 20 min in an electric furnace at 860 °C, then cooled in lead bath at

400 °C for various times to different temperatures. Lead bath has been chosen as cooling medium since residues on the work piece of any other cooling medium (e.g. salt) caused untimely damage of die and punch surface while lead acts as a lubricant. The forming part of the tool has been lubricated with colloidal graphite suspension in oil. To cool the work piece in the die, emulsion of 5%

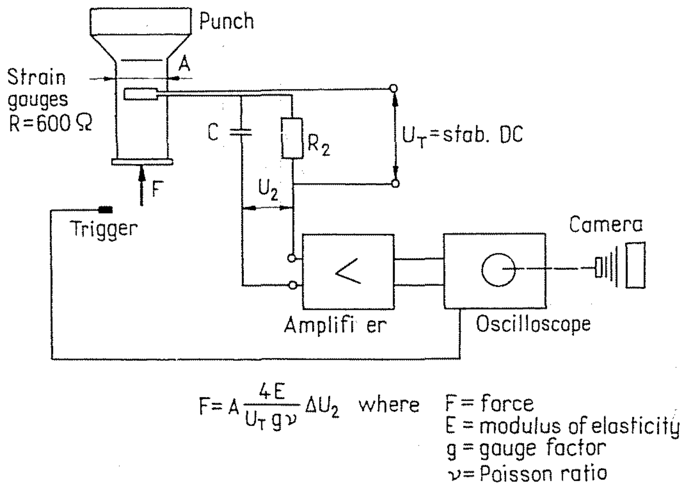


Fig. 4

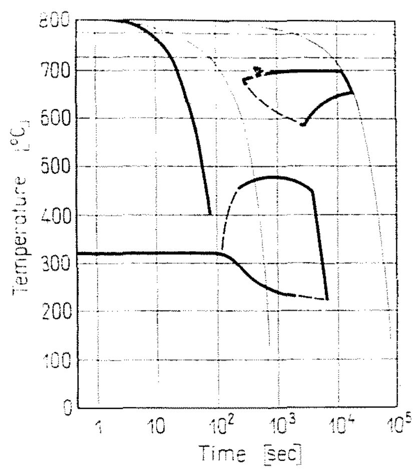


Fig. 5

soluble oil has been applied. The force needed to forming has been recorded as a function of time, using strain gauges sticked tangentially on the punch. The testing arrangement is shown schematically in Fig. 4.

The temperature of work pieces austenized and then cooled for various times has been recorded by thermocouples inserted in the billet centre. Values recorded vs. time are shown in Fig. 5, together with the continuous transformation diagram of the test material. At the beginning of deformation, the material is seen to be homogeneous austenite. Taking into account the results of DROSDOV et al. [13] who stated that the incubation time of the austenite of the material tested is reduced by 5 to 10 times in the case of upsetting, it is

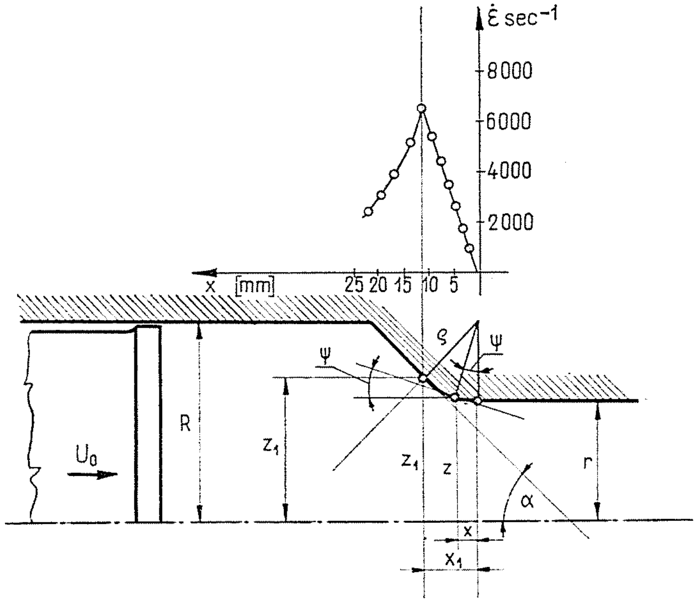


Fig. 6

obvious from the diagram that during the formation by conventional ausforming technology at low temperature the structure should be heterogeneous.

Impact energy needed to forming was altered as long as a work piece of the correct geometry resulted. The value of deformation for the extruded material part was invariably $\varepsilon = 2 \ln D/d = 1$. Deformation rate has been calculated with due regard to proportions in Fig. 6:

In the range $Z_1 > Z > R$ since $\varepsilon = \ln \frac{R^2}{Z^2}$ and $\frac{dz}{dx} = \operatorname{tg} \alpha = 1$; furthermore $\frac{dx}{dt} = u_x = \frac{R^2}{Z^2} u_0$ (u_0 being the punch rate):

$$\dot{\varepsilon} = \left| \frac{d\varepsilon}{dt} \right| = \frac{d\varepsilon}{dz} \cdot \frac{dz}{dx} \cdot \frac{dx}{dt} = \frac{2}{Z} \cdot \frac{R^2}{Z^2} u_0 = \frac{2R^2 u_0}{Z^3} \tag{2}$$

in the range $Z_1 > Z > r$:

$$\dot{\varepsilon} = \frac{2}{Z} \cdot \operatorname{tg} \psi \cdot \frac{R^2}{Z^2} u_0 = \frac{2u_0}{Z^3} R^2 \frac{\sqrt{2\varrho(z-r)-(r-z)^2}}{\varrho + r - z} \tag{3}$$

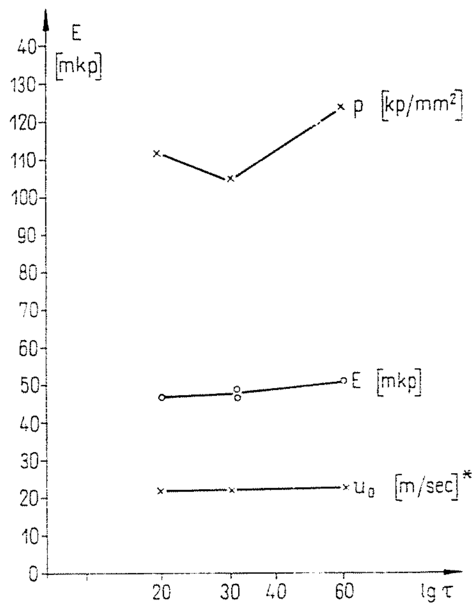
In conformity with (2) and (3), maximum deformation rate for the container geometry of the tool in Fig. 3 has been sought for, making use of a computer ODRA 1202; it was found to be at the transition part between the tapered and the rounded-off part of the tool ($Z = Z_1$), amounting, for $\varrho = 6$ mm; $r = 12.4$ mm; $U_0 = 21.7$ m/sec and $R = 20.25$ mm to $\dot{\varepsilon} = 6.272 \cdot 10^3$ sec^{-1}.

By the end of the deformation process, for $u_0 \rightarrow 0$, $\dot{\varepsilon} \rightarrow 0$. This maximum of deformation rate is higher by several orders than that applied to thermo-mechanical extrusion up to now ($2 \cdot 10^{-3} - 4 \cdot 10^1$ sec^{-1}).

Hardnesses in the meridional section of some work pieces of correct geometry have been mapped, applying Vickers hardness tests at 30 kgf load. The other work pieces have been processed into tensile specimens tested in an Instron TTD tester at 2 mm/min cross-head speed.

3. Test results

Production of work pieces of correct geometry needed $E = 4700—5050$ mkp of energy (impact rate $U_0 = 21.7 \sim 22.1$ m/sec) but slightly dependent on the overcooling time, just as did forming resistance (Fig. 7). This shows that in the zone of overcooled austenite, formed at a high deformation rate



* $u_0 = 0{,}318\sqrt{E}$ by [18]

Fig. 7

and for a given, rather high deformation value the yield stress of the material tested slightly depends on overcooling as against static test values on the common steel H11 [16].

Ready-made work pieces have bright surfaces without scaling, as scale developed in austenizing is blasted off in the lead bath. Surface roughness

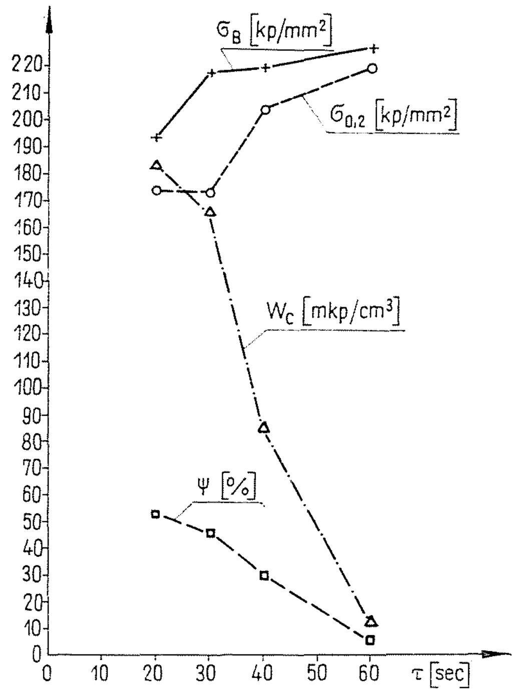


Fig. 8

value depends on the tool surface quality. A perfect polished tool may lead to $R_a < 0.6$.

Variation of strength properties vs. overcooling time is shown in Fig. 8. To evaluate strength characteristics in the diagram, some other thermal treatment technologies and thermo-mechanical treatments by rolling have been applied for the sake of comparison, compiled in Table II.

It is obvious from Fig. 8 that, provided technology parameters have been purposefully selected so that overcooling time $\tau \leq 30''$ (i.e. temperature at work-piece centre $T \geqq 544$ °C) absorbed energy to fracture $W_c = 165 \sim 185$ mkp/cm³ for a strength $\sigma_B = 218$—195 kp/mm² and a yield stress $\sigma_{0.2} =$ $= 172 \sim 175$ kp/mm² much better results can be achieved than either by

Table II

Thermal treatment or forming process	σ_B $\frac{\text{kgf}}{\text{mm}^2}$	$\sigma_{0.2}$ $\frac{\text{kgf}}{\text{mm}^2}$	ψ%	W_c $\frac{\text{mkgf}}{\text{cm}^3}$
Quenching at 860 °C + tempering at 580 °C	120	92	61.6	160
Ausforming at 860 → 400 °C $\varepsilon = 0.2$ by rolling tempering at 450 °C for 1 h	133	110	56.4	110
Isothermal quenching at —860° → 400°: for 20 sec and air cooling	126	96	46.7	102.5
High-rate thermo-mechanical forming $\varepsilon = 1$; $\dot{\varepsilon}_{max} = 6300$ sec^{-1}; $\tau = 30$ sec	218	175	45.8	166

thermal treatment or other thermo-mechanical forming methods, the more so if work piece geometry is taken into consideration. Any of the data in Table II, including those for low ausforming by rolling, are optimal, selected from a test series each.

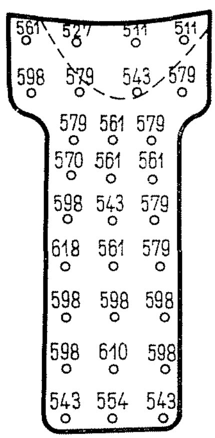


Fig. 9

Hardness map of the work piece made with optimal parameters is shown in Fig. 9. Taking the indentation size for a material of this hardness produced by a load 30 kgf together with its subjective measurement error (±42 kgf/mm² for HV — 600 kgf/mm²) into consideration, the obtained hardness distribution can be accepted as a rather uniform one.

Summary

Thermo-mechanical effects would be observed on low-alloy structural steels type NCM 15 processed by high-rate extrusion at an impact speed $U_0 = 21.7 \sim 22.1$, a deformation rate $\dot{\varepsilon}_{max} = 6300\ sec^{-1}$ and deformation value $\varepsilon = 1.0$. All these resulted in a significant strength increase as compared to conventional thermal treatment and ausforming processes. at a slight loss of ductility, where the absorbed energy to fracture the material exceeds all the values possible by any other process. At the same time, the work piece is true to geometry with a smooth surface without scaling.

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