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Original Research Article

Rheology-based approach of design the dieless drawing processes

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ABSTRACT

Dieless drawing process is based on local heating and simultaneously controlled stretching of the workpiece and allows elongation of the workpiece without using a deforming die. This process is usually used for deformation of wires, tubes and bars. The disadvantage of the dieless drawing process is the unevenness of the product diameter along its length. The present paper shows that unevenness can be substantially reduced by dividing the process into several stages. After each stage complete recrystallization of the material must be guaranteed for restoration of plasticity. The value of the strain in each stage must correspond to the area of intensive hardening on the stress–strain curve of the processed material. Thus, the proposed approach is based on the use of the special features of rheology properties of the material. The proposed approach was validated on the example of laser dieless drawing of magnesium alloy tubes.

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1. Introduction

The dieless drawing (DD) process is based on stretching the workpiece with simultaneous local heating in the deformation zone. The first studies of this process were done by Weiss et al. in paper [1] and were devoted to the production of a wire. Dieless drawing allows elongation of the workpiece without using a deforming die and lubricant. This fact is important, because in the traditional drawing process the costs of the die and lubricants are very high [2]. Usually DD is used for deformation of wires [3], tubes [4] and bars [5]. DD allows to:

- elongate the workpiece without using a die;
- change the elongation of the workpiece along its length;
- achieve large elongation in one pass.

The sources of local heating are electric furnace, inductor or laser beam. In the latter case the process is called laser dieless drawing (LDD) [6].

The literature on DD highlighted that the main disadvantage of this technology is the instability during the process [2], which leads to result undesirable irregularity of the diameter of the product along its length (IPD). This problem is important because it affects the quality of products, but it is also related to the technological plasticity of the material. In DD the fracture mechanism is analogous to fracture during the tensile test and is associated with the formation of the neck, i.e. with IPD.

Most studies in the field of IPD have focused on experimental observations only. Authors of [3] examined the trend in IPD as function of process parameters. It was shown that the

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IPD of the wire after DD increases with elongation. In paper [5] it was shown that when the speed of the process increases, IPD of the bar after DD decreases. During DD of tubes, IPD also increases with elongation. It is shown in [7] that when the elongation reaches more than 30–35%, the IPD increases even more intensively. The technological solution of this problem was proposed in [8]. It consists of the use of a system of continuous measurements of the current diameter and of the appropriate control of the process parameters. However, this approach did not explain the nature of the initiation of IPD and solved the problem solely by the methods of automatic control. Together, these studies indicated that problem of IPD is one of the important limitations of the DD process.

Since in the process of DD the deformed state is close to linear stretching, it can be assumed that the mechanisms of neck formation during tensile test and the instability during DD are similar to each other. A general criterion for rod necking during tensile test is Armand Considère criterion for plastic instability [9]:

$$\sigma = \frac{d\sigma}{d\epsilon} \tag{1}$$

where: σ – flow stress, ε – effective strain.

The basis of this criterion is that necking will not occur until the applied stress reaches the value of the slope of the stress strain curve.

The flow stress σ depends on temperature t, effective strain ε and strain rate ξ, consequently:

$$\sigma = \frac{d\sigma}{d\epsilon} = \frac{\partial\sigma}{\partial t}\frac{\partial t}{\partial\epsilon} + \frac{\partial\sigma}{\partial\xi}\frac{\partial\xi}{\partial\epsilon} + \frac{\partial\sigma}{\partial\epsilon} \tag{2}$$

Therefore, material with intensive strain hardening is less prone to neck formation. As follows from Eq. (2), one of the possibility of improving stability in the DD process is to increase $\partial\sigma/\partial t$ by rapidly cooling the deformation zone. This method is used, for example, in work [10]. The increase in parameter $\partial\sigma/\partial\varepsilon$ is difficult to realize, since it is limited by the rheological properties of the material. On the other hand, these criteria do not take into account the features of the DD process, for example, the non-uniform temperature distribution in the deformation zone. For this reasons, it is still not used in practice to improve the stability of DD processes.

In paper [11] a stability criterion for the DD process was proposed:

$$\gamma + m + \beta\frac{d\ln t}{d\ln A} \leq 1 \tag{3}$$

where γ is the strain hardening coefficient, m – the strain rate sensitivity coefficient, β – the temperature coefficient of flow stress, t – the temperature of the deformation zone, and A – the area of any section in the deformation zone.

However, this criterion, cannot be used directly for prediction of instability, because distributions of strain, strain rate and temperature during DD are very complicated. This is noted, for example, in the paper [12]. As alternative to the use of this criterion, in paper [12] an experimental study was used to determine processing limit maps for the stable deformation during DD.

Beyond this, previous studies show that the features of strain hardening of the material are still not used in practice to stabilize DD processes and to improve the undesirable unevenness of the product diameter along its length.

The purpose of this paper is to study the relationship between the propagation of IPD, the features of strain hardening of material and parameters of the DD. The specific goal of this study was to propose a new approach to the development of DD processes based on the features of strain hardening of the material and the FEM model. This approach does not negate the possibilities of hardware automatic control, but it allows choosing the process conditions which provide IPD decreasing in a natural way.

2. Theoretical approach

The proposed concept of reducing IPD for tubes or wires during DD was based on the observed regularities of the neck formation during tensile tests. The process of neck formation under tension is determined by the shape of the stress–strain curve of the material for these deformation conditions [13].

There may be several reasons for the initial IPD, for example:

- Initial uneven distribution of diameter as a result of previous processing;
- Uneven distribution of temperature or mechanical properties.

However, under intensive strain hardening of the material, a mechanism for compensating these factors will become active. Hardening will occur in the place of initial strain localization (this corresponds to a local reduction in diameter). In consequence, the hardening hinders further localization of deformation and reduces IPD.

Thus, the main element of the concept is the analysis of the rheological properties and intensity of hardening of the material. Since the stress-strain curves usually have a relatively small part with intensive hardening, favorable deformation conditions are limited by a small deformation. This leads to the following conclusions:

1. To achieve large elongations and minimization of IPD, it is necessary to perform several passes. The magnitude of the strain in each pass must not go beyond the area of intensive hardening of the material.
2. Between the passes, the plastic properties of the material must be restored. This will again use the initial part of the stress-strain curve with intensive hardening. It was assumed that complete recrystallization after the previous pass is a sufficient condition for restoring the properties of the material.

Under local heating of the deformation zone with temperature gradient along the workpiece in the DD process, neck formation is more likely to happen than during the tensile test. Thus, the hardening curves cannot be directly used to

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