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Deep drawing failure modes

AV Nezamaev[1, 2] and V V Karzhavin[1]

[1] Department of Metallurgical and Rotary Machines, Ural Federal University named after the First President of Russia B N Yeltsin, 19, Mira str., Yekaterinburg, 620002, Russia

E-mail: [2] alexei.nezamayev@gmail.com

Abstract. In this paper, we have presented various technological process conditions leading to the damage of workpieces or the manufacture of low-quality pieces during deep drawing of metal sheets. All the conditions, resulting in failure modes, have been included in the general classification. According to this classification, there are three main directions of potential failures: complete or partial fracture, buckling or wrinkling, and surface damage. The rigorous relations between production parameters and possible negative consequences have been also given. For the first time, the different aspects of such an issue have been considered together. Thus, we have takenthe first steps towards creating a reliable system for assessing the risk of complex failures in obtaining deep-drawn products (caused by the impact of several reasons at the same time).Having developed this system, we wouldfacilitate the advancement of deep drawing technology and it might well open up new horizons for the deep-drawn products of unrivalled quality without rejections, equipment breakdown, emergency downtime, etc.

1. Introduction

It is well known that deep drawing is a sheet metal forming process, which allows obtaining large lots of hollow thin-walled metal products within a short period. Though the method itself is highly beneficial, the specificity of the technological process makes it extremely sensitive to numerous parameters. To date, optimal parameter values have been determined for many state-of-the-art types of deep drawing and these data are readily available. However, when some process characteristics become unacceptable due to specific circumstances, it inevitably results in the production of the items, which do not meet the requirements of the quality standards. Moreover, the same conditions can lead to some kinds of fracture inherent for deep drawing [1].

Aiming to develop a convenient risk assessment tool for the detection of failure modes beforehand with high probability, and in order to determine failure problems online during the drawing process, the conditions mentioned above were generalized under the concept of ‘Deep Drawing Failure Modes’ and their classification was proposed as follows: complete or partial fracture, buckling or wrinkling, and surface damage.

The main points of the deep drawing failure modes have been presented in this paper. Corresponding preconditions and mathematical expressions of the assessment criteria have been placed according to the particular type of failure.

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2. Classification of deep drawing failure modes

2.1. Complete or partial fracture

2.1.1. Tearing sidewalls near the base of drawn cups. Significant sidewall thinning is frequently observed during deep drawing, which may lead to workpiece tearing failure. It usually occurs at the so-called weakest section, namely the region near the base of the drawn cup. It is explained as follows. At the initial phase of the process, this region is placed above the clearance between the die and the punch. When the punch draws the blank into the die, this region is not subjected to hardening through the bending over the die edge. Further, this annular region shifts towards the power transition section, becoming thinner due to tensile stresses inducing their subsequent growth. Obviously, the equality of the tensile stress to the tensile strength can be accepted as a precondition for this type of failure [2].

Besides deviation from optimal values of technological parameters and the deterioration of material properties, tearing may occur during multistage deep drawing of wide-flange components if the material volume of the cup drawn at the first stage is not enough for the next stage.

2.1.2. Cracking the upper part of workpieces during redrawing. The walls of redrawn parts are subjected to tangential tensile stresses – both the residual stress and the stress resulting from bending over the die profile. Furthermore, the material of the workpiece's upper part possesses lowered strength characteristics due to the presence of microcracks at the workpiece rim, and, in addition, it is hardened. Therefore, it is supposed that fracture occurs before the tensile stress value becomes be equal to the tensile strength. The criterion for this type of failure depends on stress efficiency parameter K_{1C} [3], microcrack length *l*, residual tangential stressσ_θ^R, tangential stress resulting from bending over the die profile σ_θ^M, and Poisson's ratio *ν*. Thus, this criterion is reckoned by the following formula [4]:

$$\sigma_\theta^R + \sigma_\theta^M = 0.9\, K_{1C} \left(\frac{1-\nu^2}{\pi l}\right)^{1/2} \quad (1)$$

The maximum permissible microcrack length can be obtained from equation (2)

$$l = \frac{0.26 K_{1C}^2 (1-\nu^2)}{\left(\sigma_\theta^o + \sigma_\theta^M\right)^2} \quad (2)$$

It should be noticed that this type of failure is the most typical one for multistage drawing without intermediate annealing.

2.1.3. Delayed cracking of intermediate and end products during storage. In contrast to cracking of the upper part of a blank during the drawing process, delayed cracking may occur in the absence of any external loads. In the latter case, the failure is related to the phenomenon of hydrogen-induced embrittlement. The initiation and development of the cracking process are caused by the diffusion of hydrogen towards high-tensile stress regions [5].

Pearlite and ferrite-pearlite steels, containing up to 0.2 % carbon, are least prone to delayed cracking failure, whereas steels with a martensitic structure are the most susceptible to the failure. The usage of deep drawing for austenitic steel treatment increases the probability of the subsequent delayed cracking at low levels of austenite stability. The presence of a strain-induced martensitic phase can lead to the initialization of cracking. The period between the initialization of the process and the cracking itself may last from an hour to a few days [6]. Under certain conditions, if a corrosive medium affects the material, this type of failure can be considered as stress-corrosion cracking.

Summarizing all the above, we can point out the following precondition of delayed cracking: residual stress, sufficient content of hydrogen in alloys or favorable conditions for its increase (corrosive medium, for example, a lubricant with chlorine content even when it deals with stainless steel), the capability of hydrogen to diffuse through the material, prolonged time of product storage before annealing.

2.2. Buckling and wrinkling

2.2.1. Workpiece buckling during deep drawing with pushing force applied. As it was mentioned in the first subsection, tearing occurs in the weakest section of the workpiece during the drawing of wide-flange components due to the shortage of material volume in the cylindrical part of the wide-flange piece after the first stage of drawing. To avoid this type of failure, deep drawing with axial pushing force is utilized.

In this case, the main limiting factor is the axial buckling of the workpiece shape upon axial compression. As a result, both complete buckling and local periodical buckling are possible. The latter leads to the formation of specific ridges on the walls of products that negatively affects their mechanical characteristics. The criterion of this failure is the value of pushing force, which exceeds the value of the critical force for certain conditions. In [7], the formula (3) was proposed for the estimation of this critical stress:

$$\frac{\sigma_{cr}}{\sigma_s} \approx \frac{0.5}{\sin\frac{\alpha_i}{2}}\sqrt{\frac{h}{R_z}} \tag{3}$$

where σ_{cr} – critical stress, σ_S– yield strength, α_i– input angle, h – wall thickness, R_z– radius of the non-drawn part of the workpiece.

It should be taken into account that the pushing force is also dependent on the friction condition at the die entrance. Thus, it should also be considered as a precondition of buckling.

2.2.2. Wrinkling. At the first stage of drawing without blank holder, the flange stability, the condition obtained by Shoffman [8], is determined by the equation (4):

$$\frac{t_0}{D_0}100 \leq 4.5(1-K_1) \tag{4}$$

where t_0 – workpiece thickness, D_0– workpiece diameter, K_1– the ratio of the product diameter to the workpiece diameter (drawing ratio).

When the requirement is fulfilled, circumferential compressive stresses, arising from a decrease in workpiece diameter, only leads to an increase in workpiece thickness. When the requirement is not fulfilled, along with an increase in thickness, the formation of a fold (wrinkles) is also possible [9]. Moreover, it was found in [8] that the tendency to fold formation is higher for intensely hardening metals.

While drawing with blank holder, the loss of flange stability may still occur. In this case, the precondition for buckling will include a blank holder parameter. Depending on its design, this can be rigidity, pressure or the gap size between the blank holder and the die [9].

2.3. Surface damage

In most cases, the surface damage is a consequence of adhering blanks to drawing tool surfaces, which is possible when a positive gradient of the mechanical properties of treated materials is not maintained. The main reason for the occurrence of such defects is breaking down the lubricating film, which takes place upon the improperly chosen set of parameters: contact pressure, temperature, lubricant, and deformation rate (or an unexpected change in these parameters) [10].

As it was shown in the study [11], ceteris paribus, the specific amount of heat released per unit time rises with the increase of the workpiece diameter (it is so-called size factor), which explains the fact that suitable friction conditions more frequently cannot be maintained during large-size pieces treatment due to a higher temperature in contact zone when compared to drawing small-size components while drawing ratio is kept the same.

High friction coefficients are observed at both extremely high and extremely low surface roughness values. In the first case, it can be explained by breaking down the lubricant film on a coarse surface. In the second case, it may be attributed to the absence of surface cavities to hold up the lubricant [12]. It is worth mentioning that, in the latter example, the adhesive component of friction force may also increase [13].

Besides the stability of lubrication films, it is necessary to take into account its ability for self-recovery, which is higher for liquid lubricants than for solid ones. In this connection, it is recommended to utilize lubricant compositions containing both solids for coating protected surfaces and a liquid layer for lubrication [11].

3. Conclusion

In the paper, we elaborated the classification of failure modes taking place in deep drawing processes. It includes the criteria of failure occurrence and the consequences leading to certain defects of products. For every type of failure, we determined the preconditions for its occurrence. Their mathematical interpretations were also given. This classification may be useful in assessing the reliability of the production process. We plan to use the revealed failure modes in further research, which will include the following steps: the study of each type of failure separately and with respect to specific materials; the determination of relationships between parameters involved in this process; the clarification of failure criteria; the development of measures for preventing and eliminating failures; the development of deep drawing technology with minimal failure probability. We expect that these data will be useful for failure risk assessment at the development stage of the manufacturing process to avoid rejects, equipment breakdown, emergency downtime, and so on.

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