Induction heat treatment of steel punches with Zr-containing coatings and preliminary results of FLD characteristics when drawing C45 carbon steel

A Fomin¹, V Koshuro¹, A Shumilin¹, A Voyko¹, P Palkanov¹, A Aman², N Mukhin³, S Palis²
¹Yuri Gagarin State Technical University of Saratov, Saratov 410054, Russia
²Otto-von-Guericke University, Magdeburg 39106, Germany
³Otto Vollmann GmbH & Co. KG, Gevelsberg 58285, Germany
⁴Saint Petersburg Electrotechnical University, Saint Petersburg 197022, Russia

Abstract. The paper presents data on strengthening induction heat treatment (IHT) of die tools (punches) and production of wear-resistant Zr-containing coatings on their surfaces. Preliminary results were obtained on the forming limit diagrams (FLD) during drawing (Nakazima's test) of sheet C45 carbon steel. It was established that punches with Zr-containing coatings after IHT had better characteristics for stretching compared to the uncoated tool steel.

1. Introduction
In metalworking, in particular shaping operations of sheet-metal forming, it is important to determine the ultimate strains that can be perceived by metal [1,2]. The main characteristic describing the deformation ability of any metal and alloy is a forming limit diagram (FLD) or a forming limit curve (FLC). To determine FLD Nakazima's test is conventionally used, which provides for the application of a punch with a hemispherical working part (ISO 12004-2: 2008).

In the "punch – sheet metal" system, it is necessary to ensure maximum stretching at minimum stresses without the formation of defects, such as cracks, tears and folds (Figure 1).

It is known that wear-resistant coatings, e.g. nitrides, carbides and carbonitrides, as well as diamond-like films, are deposited on the surface of the steel die tools to reduce the force of friction and improve the drawing characteristics [3]. However, there are experimental results according to which it is possible to use oxide coatings, in particular titanium oxide [4,5], in order to increase wear resistance and improve the functional qualities of the metalworking tools (replaceable plates of cutters). Also, to improve the friction conditions, it is necessary to choose a lubricating fluid or use a coating with a solid lubricant disulfide of MeS₂ metals [2].

Thus, in this paper, the hardness of the coatings produced on steel punches was studied and the preliminary FLD data for the drawing (Nakazima's test) of carbon C45 steel sheet were determined.

2. Methodology
Steel punches made of high carbon U8 tool steel (analogue of C80W1) were subjected to induction quenching (from a temperature of 1200 °C) with self-tapping to ensure a hardness of at least 59–60 HRC.
Next, a thin zirconium coating with a thickness of about 0.8 μm was applied using PVD (DC-mode) onto the surfaces of the punches previously prepared by grinding to ensure the roughness $Ra = 0.16$. A strengthening induction heat treatment (IHT) was performed to obtain an oxygen-saturated layer with high hardness (Figure 2a). The processing temperatures were 400 and 550 °C at an exposure of not more than 300 s. At a higher IHT temperature, these coatings cracked, which precluded their use as a wear-resistant layer for the punches.

![Image of FLD and main areas]

**Figure 1.** FLD and main areas: I – zone of destruction; II – unacceptable thinning; III – the risk of breaks; IV – without defects; V – the risk of folds; VI – the appearance of folds; FLC – the resulting curve.

The microhardness of the zirconium-containing layer on the surfaces of the punches was specified using a "PMT-3" hardness tester with loads on the Vickers diamond indenter of 50 gf.

The drawing test (according to Nakazima's scheme) involved the manufacture of 1 mm thick discs with a diameter of 44±0.2 mm and made of C45 steel with edge cuts of different radii $R$ from 0 to 20 mm. A grid of small pitch of 1–1.5 mm was applied to the surface of the discs with the help of a laser for subsequent control of the deformation using an "AGPM-6M" geometric parameters analyzer.

The prepared samples were placed in a stamp consisting of the upper and lower halves (Figure 2b). The replaceable part was connected to the tool shank and installed in the die hole. The stamp assembly was installed in a hydraulic press, which provided a force of at least 10 tf.

The measured deformations in the form of a cluster of points were plotted on a diagram, through which an FLC was drawn. Next, the curves were plotted on one graph for subsequent comparison of the functional characteristics of the uncoated punches and those with wear-resistant coatings.
3. Results

The hardness of zirconium coatings reached a moderate value about 420–450 HV. The resulting value was not enough to increase wear resistance, therefore, of practical interest were the coatings after strengthening IHT. The hardness of zirconium-containing coatings after IHT reached 670–700 HV, which was equivalent to 59–60 HRC.

![Figure 2(a,b).](image)

Figure 2(a,b). The location of the punch with a coating 3 in a quartz chamber 2 of a copper inductor 1 (a); the location of a matrix 6, a shank of the punch 5 and a stem of the press 4 during drawing (b).

The resulting thin coating improved the drawing characteristics, in particular the limiting deformation exceeded 40 % at major strain $\varepsilon_1$ and reached 35 % at minor strain $\varepsilon_2$ (Figure 3, curve 3). The uncoated punch had lower characteristics for drawing, i.e. its $\varepsilon_1$ and $\varepsilon_2$ did not exceed 25 % (Figure 3, curve 1). For the stretch region (left half-plane of the diagram), good results were also observed for zirconium-containing coatings after the IHT (Figure 3, curve 3,4). The ultimate deformation reached from -5 to -10% in major strain $\varepsilon_2$.

However, the FLC data should be investigated in conjunction with the data of drawing force, which were determined when analyzing the drawing diagrams. The pressing force was also reduced when using the punches with IHT coatings. The maximum stresses at the drawing did not exceed 22 kN and for the coated punches this value was lower on average by 0.5–1 kN.
Figure 3. FLC for various punches: 1 – 1.3343 tool steel (uncoated); 2 – Zr coating on C80W1 tool steel; 3 – Zr+ZrO$_2$ (IHT-modification at $T = 400$ °C); 4 – Zr+ZrO$_2$ (IHT-modification at $T = 550$ °C)

4. Conclusions
Thus, zirconium-containing punches after IHT provided improved FLD characteristics for the drawing process. An increase in the hardness and oxygen content of the wear resistant coating improved the deformability of structural C45 steel from 25 to 35–40 %.

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