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Investigation of the Change in the Magnetic Properties of Die Steels in the Process of Manufacture and Operation of Die Tools

I I Karpukhin[1], A I Selishchev[2], A V Kornilova[1, 3], I M Idarmachev[4]

[1] ZAO Prochnost, 8A, Ryazansky prospect, Moscow, RU-109428, Russia
[2] AO KBAL im. L.N. Koshkina (Koshkin Engineering Center for Automated Lines), 21A, Prospect 50 let Oktyabrya, Klimovsk, RU-142184, Russia
[3] RUDN (People's Friendship University of Russia), 6, Miklukho-Maklaya str., Moscow, RU-117198, Russia
[4] FGOU FPO MGTU Stankin (Stankin Moscow State Technological University) 3A, Vadkovsky pereulok, Moscow, RU-127055, Russia

E-mail: karpukhin.iv@yandex.ru

Abstract. The paper presents the results of the investigation of the change in the coercive force in the materials of the die tool working parts during manufacture and operation of die tools; the paper offers possibilities of application of testing based on the coercive force.

The main problem stamping plants are facing is short lifetime of die tooling. Dies have complex shape and are subject to significant cyclic mechanical loads, and in case of hot stamping - also to temperature loads. Short service life of dies results in considerable production losses due to the equipment downtime caused by the change of stamps (or their working parts) and increased expenses for the equipment setup. Failures of die tools often cause emergencies on the shop floor and injuries to operating personnel. Die tooling lifetime is influenced by a large number of factors (equipment design and wear degree, process step load chart, design and running hours of a tool, etc.) and can vary significantly. A common technique to accurately determine a service life of a die tool has not been developed so far. The data given in the classical technical literature are empirical and approximate. There is no precise calculation method. The difficulty of estimating the tooling service life lies in the fact that the tool operation is almost always accompanied with a combined action of several destructive processes, which may both decelerate and significantly accelerate each other at different stages of the tool operation.

Therefore, it is required to identify a testable parameter to monitor the tool material condition in order to be able to take a tool out of service before it starts deteriorating. We propose to use the coercive force as such a parameter to monitor the die tooling condition [1]. The mechanism of change in the characteristics of the hysteresis magnetic loop under the influence of external or internal factors is based on the force and energy interactions of domain boundaries moving during remagnetization of a ferromagnetic with defects of a crystal lattice, with the contribution of electrons of incomplete *d*-shells of atoms to the generation of interatomic bond forces [2, 3], etc. Because of this, any loading of

the interatomic bond forces caused by mechanical or thermal influences has an immediate impact on the magnetic properties of metal [4, 5]. This phenomenon has found use in non-destructive testing [6-8].

At present, diagnostics based on the use of the coercive force is exceptionally rare in die forging. This method is mainly used for testing hardness of the deforming tools, see papers [9, 10]. The purpose of this work is investigation of the change in the magnetic properties of die steels in the process of manufacture and operation of die tools and development of engineering foundations for diagnostic techniques based on the coercive force to assess the condition of cold sheet metal stamping dies and hot forging dies. Such techniques will make it possible: to determine the tool service life quickly and efficiently, to set the frequency of scheduled repairs, to mitigate economic risks for a company.

To check whether it is possible to monitor the condition of steels used for manufacture of cold stamping dies and hot forging dies with the use of magnetic methods we used the Schaeffler diagram [11], which represents the relation between the content of alloying elements in steel and its phase composition.

Alloying elements can be conditionally divided into two groups according to their influence on the phase composition, and, consequently, on the magnetic properties of steels. The first group includes elements which increase the magnetic permeability and reduce the coercive force. For this group, chromium equivalent m_{Cr} (%) is calculated using the formula [11]:

$$m_{Cr} = Cr + 1.5 \cdot Si + Mo + Nb , \tag{1}$$

where *Cr*, *Si*, *Mo* and *Nb* is percentage content of chromium, silicon, molybdenum, niobium, respectively. The second group includes elements which decrease the magnetic permeability and increase the coercive force. For this group, nickel equivalent m_{Ni} (%) is calculated using the formula [11]:

$$m_{Ni} = Ni + 0.5 \cdot Mn + 30 \cdot C , \tag{2}$$

where *Ni*, *Mn* and *C* is percentage content of nickel, manganese and carbon, respectively.

The calculation was performed for tool steels used for cold stamping (U10, U10A, U13, U13A, Kh12MF, 40Kh5MF, 27Kh2N2M1F, 8Kh4V3M3F2, 7KhG2VMF, KhVG, 9KhVG, 6KhS, 6KhVG, 4KhV2S) and hot forging (3Kh2V8F, 3Kh3M3F, 4Kh2V2MFS, 4Kh2V5MF, 4Kh2NMF, 4Kh3VMF, 4Kh4VMFS, 4Kh5V2FS, 4Kh5MF1S, 4Kh5MFS, 4KhMNFS, 4KhMFS, 5Kh2MNF, 5Kh3V3MFS, 5KhGM, 5KhNV, 5KhNVS, 5KhNM, 7Kh3, 8Kh3). The average values of chemical elements content specified in the corresponding regulatory documents were used for the calculation. Analysis of the results obtained with the use of (1) and (2) and plotted on the Schaeffler diagram showed that most tool steels have martensite-austenite structure, which means that magnetic methods can be used to monitor condition of such steels.

In order to check this conclusion we performed monitoring of 20 shearing dies for cold sheet metal stamping (to make a representative sample of the values received at the three plants where these dies are used in open crank presses). It should be noted that all the plants where we conducted experiments purchased tool steels from the same steel works (Zlatoustovsky Steel Works) and applied the same heat treatment process prescribed by the technical documentation. The coercive force H_c (A/m) was the main controlled parameter. The rated force of the presses varied from 125 to 500 kN; the tensile strength of the blank material varied from 450 to 930 MPa, the tensile strength of the female die material ranged from 1,235 to 2,550 MPa, the number of regrindings of the die being tested was from 0 to 2, the number of parts made with the die at the start of the testing varied from 0 (a new die) to 102,991. These factors were selected as the ones with most influence on the change in the coercive force in the die working parts and the ones that can be most reliably determined in the plant conditions. During the experiments we measured the coercive force in two mutually perpendicular directions at intervals equal to a certain number of loading cycles specified according to the capabilities of the real production facilities. Figure 1 shows one of the tested dies in the working area of the press. It was established that on repeated exposure to mechanical stress (without thermal cycling) the coercive force in tool steels increased. The coercive force gain was taken as a damage

indicator. The rate of its growth depends on the level of stress applied. The experiments show that an increase in stress by 13 MPa leads to an increase in the damage accumulation rate (by the growth of the coercive force) by a factor of 1.3.
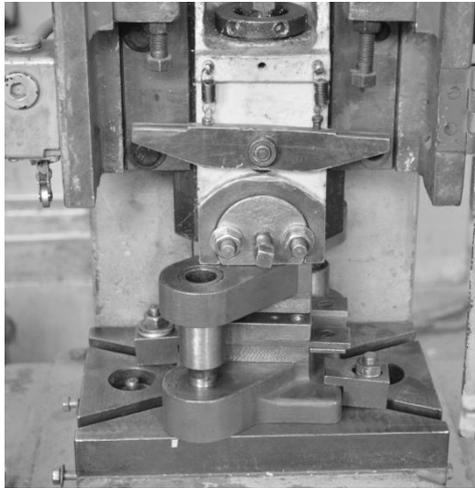
Figure 1. Sequential cold sheet metal stamping die in the working area of the press.

The coercive force growth rate during cyclic loading in cold sheet metal stamping female dies (limiting the life of a die in most cases) is described by the following mathematical models:

$$\frac{dH_c}{dn} = 0.85 \cdot (7 \cdot 10^{-5} \cdot X_1^2 - 0.073 \cdot X_1 + 19.105) \cdot (2 \cdot 10^{-6} \cdot X_2^2 - 0.008 \cdot X_2 + 8.816) \times$$
$$\times (0.520 \cdot X_3^2 - 0.729 \cdot X_3 + 0.651) \cdot (3 \cdot 10^{-10} \cdot X_4^2 - 3 \cdot 10^{-6} \cdot X_4 + 1.077) \times \tag{3}$$
$$\times (-0.142 \cdot X_5^2 + 0.652 \cdot X_5 + 0,186) \cdot (7 \cdot 10^{-6} \cdot X_6^2 - 0.005 \cdot X_6 + 2.321);$$

$$\frac{dH_c}{dn} = 0.95 \cdot (10^{-4} \cdot X_1^2 - 0.112 \cdot X_1 + 29.160) \cdot (5 \cdot 10^{-6} \cdot X_2^2 - 0.017 \cdot X_2 + 14.282) \times$$
$$\times (-0.024 \cdot X_3^2 + 0.384 \cdot X_3 + 0.642) \cdot (2 \cdot 10^{-9} \cdot X_4^2 - 10^{-4} \cdot X_4 + 0.129) \times \tag{4}$$
$$\times (-0.064 \cdot X_5^2 + 0.379 \cdot X_5 + 0.465) \cdot (5 \cdot 10^{-5} \cdot X_6^2 - 0.025 \cdot X_6 + 4.648),$$

where n is the number of the tool loading cycles; X_1 is the tensile strength of the blank material, MPa; X_2 is the tensile strength of the female die material, MPa; X_3 is the number of the tool regrindings; X_4 is the number of parts made with the die at the start of the testing; X_5 is the blank thickness, mm; X_6 is the rated force of the press, kN.

Equation (3) describes the change in the speed in the direction of measurement along the front edge of the press, equation (4) – perpendicular to the front edge of the press. Adequacy of models (3) and (4) to the experimental data is proved by the fact that the Theil coefficient is close to zero (0.065 for (3) and 0.124 for (4)). Based on the results of the research conducted, we developed a method and technique for determination of the life of tools operating under time-varying stresses (without contribution of thermal cycling towards the deterioration process) [12].

Until recently, the very possibility of using magnetic testing to estimate the service life of tools for hot forging has been questionable. At present, it is known that magnetic properties are sensitive to transformations that occur in metal during thermal cycling. This is confirmed by the results of our investigations of the magnetic properties of dies for hot forging and thixotropic stamping. We examined the coercive force of hot forging hammer dies of steel grades 5KhNV and 5KhNM for forgings of various configurations. Whenever possible, we took measurements at all stages of manufacture and operation of the die tools. In addition, we measured hardness in the same points with the use of a portative TEMP-4 hardness gauge. In parallel, the stamping process was calculated using the Deform-3D software according to the production process established for the tested dies and with

regard to the features of the applied equipment. The calculation gave us the stress and temperature distribution in the dies at the characteristic moments of stamping.

Next, we made samples of the measured values of the coercive force and calculated values of the maximum normal stresses and temperatures in the corresponding points of the die working cavity for each tested die condition. We used the stress and temperature values for the final step of calculation of the last stroke during stamping/sizing. For the die condition before stamping-sizing operations (at the stage of machining and heat treatment) we used the stress and temperature values typical for the same points of the die working cavity at the subsequent operation (stamping or sizing). Next, using Brandon's method [13] we approximated the coercive force values by the stress and temperature modules with the use of linear functions. This solution makes it possible to receive a clear picture of the coercive force distribution over the die surface and to monitor the coercive force changes depending on the loading level of the die working cavity areas during stamping operations.

Figure 2 (b) and (c) shows the obtained calculated dependences of the coercive force in the upper die for a "fork" forging. Measurements were taken for the die in a quenched condition before its operation and in a weakened condition after its operation and reworking. A 2-3-fold reduction in the coercive force between the measurements was recorded, with the coercive force being distributed more uniformly over all the points of the die working cavity after the processing. Figure 2 (d) shows a diagram for this die after quenching and stamping of 1,963 forgings. As can be seen from the diagram, there is a significant increase in the coercive force. In addition, we took measurements for the sizing
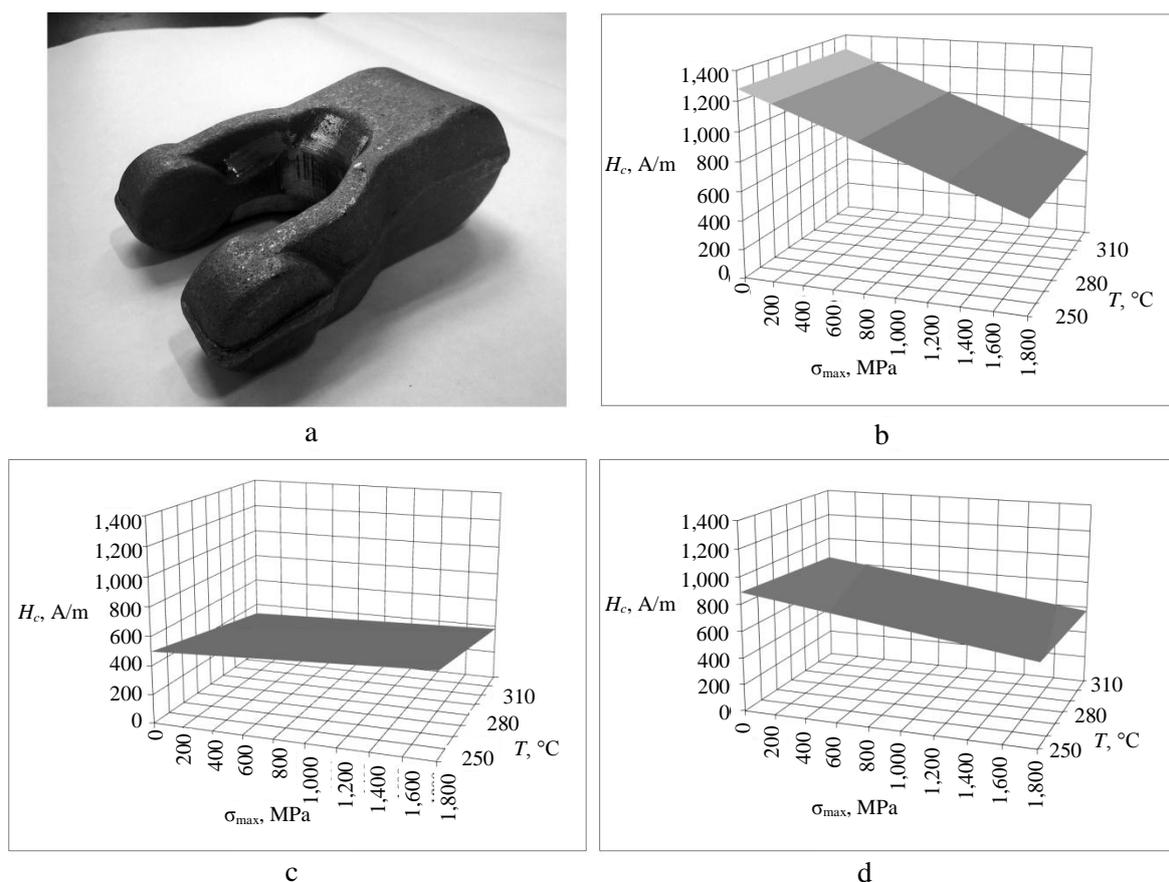
Figure 2. Dependences of the coercive force on temperature and stress for the upper die for a "fork" forging (a) in a condition: (b) before operation, (c) after stamping of 1,530 forgings and reworking, (d) after stamping of 1,963 forgings; die material – 5KhNV steel grade.
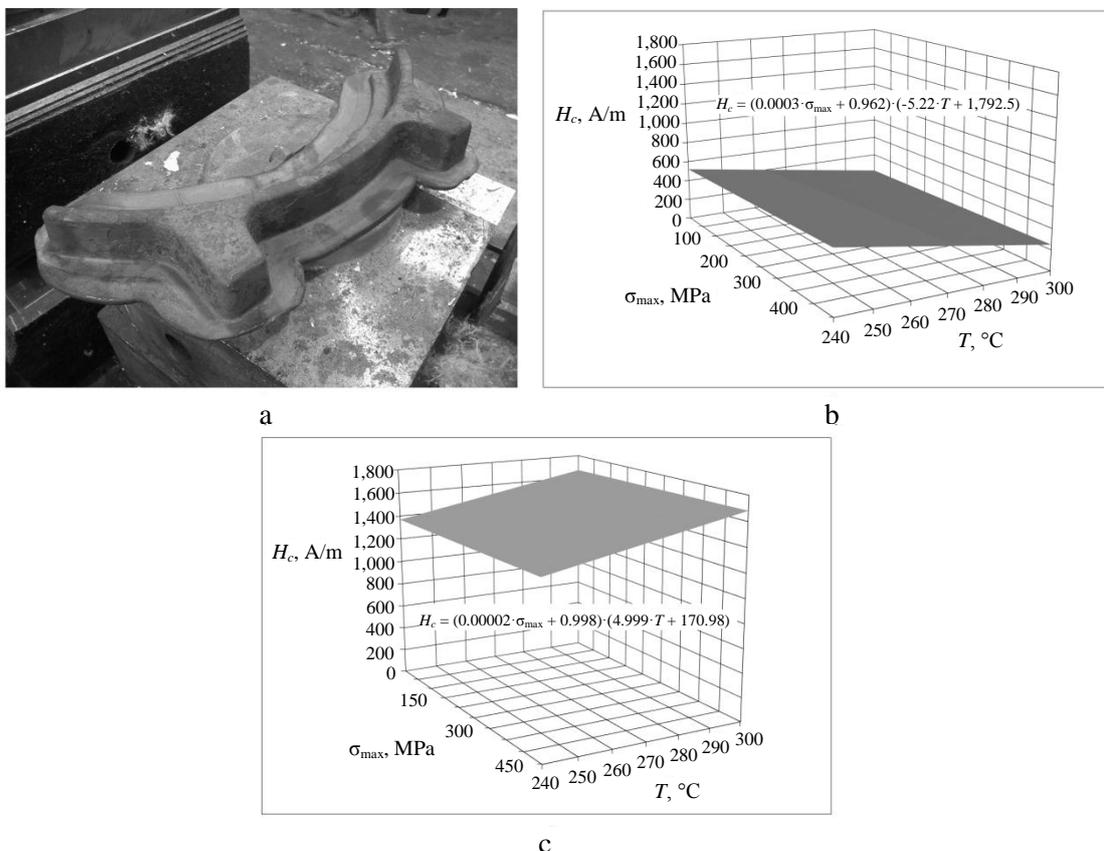
lower die for a "hoop" forging in a condition before quenching and in a condition after quenching and tempering with short time in operation. We recorded a 3-4-fold growth in the coercive force between the measurements. During annealing of steel a grain growth is observed, which is accompanied by a reduction in the total length of grain boundaries, which prevent displacement of domain boundaries, and, as a result, the coercive force decreases. Quenching, on the contrary, is accompanied by an increase in the length of grain boundaries due to formation of fine structure with precipitation of free carbon and carbides, which leads to the coercive force growth.

Figure 3 shows the surfaces of the sizing lower die for a "hoop" forging in a condition before quenching and in a condition after quenching and tempering with a small number of loading cycles. A 3-4-fold growth in the coercive force between the measurements was recorded. During annealing of steel a grain growth is observed, which is accompanied by a reduction in the total length of grain boundaries, which prevent displacement of domain boundaries, and, as a result, the coercive force decreases. Quenching, on the contrary, is accompanied by an increase in the length of grain boundaries due to formation of fine structure with precipitation of free carbon and carbides, which leads to the coercive force growth. The property of the coercive force to change during heat treatment is used in industry to control heat treatment quality and to determine steel hardness. In order to identify dependencies between the hardness and the coercive force of steel grades 5KhNV and 5KhNM, the approximate Brinell hardness HB for steel grade 5KhNV by the coercive force value H_c (A/m) may be determined using the formula:

$$HB = 0.0754 \cdot H_C + 259.3 ; \tag{4}$$

hardness HB for steel grade 5KhNM – using the formula:

$$HB = 0.095 \cdot H_C + 219.1 . \tag{5}$$

Figure 3. Dependences of the coercive force on temperature and stress for the sizing lower die for a "hoop" forging (a) in a condition: (b) before quenching, (c) after quenching and tempering and calibration of 90 forgings; die material – 5KhNM steel grade.

The obtained models are adequate to the experimental data by the Fisher's criterion with a significance level of 0.01. It is obvious from (4) and (5) that the hardness and the coercive force of steel grades 5KhNV and 5KhNM are almost in a direct relationship to each other.

Figure 4 shows a calculated diagram for the die for a "hoop" forging. This die cracked during heating. The low value of the coercive for steel grade 5KhNV suggests that the die has been in operation for a long time. The lowest values of the coercive force are recorded in the loaded areas.

a   b
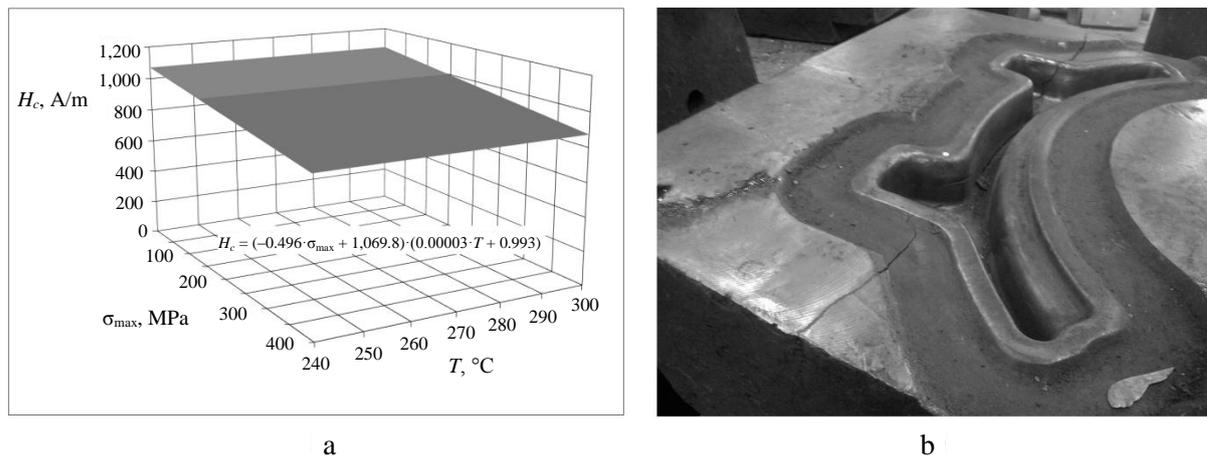
Figure 4. Dependence of the coercive force on temperature and stress (a) for the cracked lower die for a "hoop" forging (b); die material – 5KhNV steel grade.

Conclusions.

1. The experiments with cold sheet metal stamping dies have shown that the coercive force in all elements of dies in two mutually perpendicular directions of the coercive force measurement is unequal. The magnetic properties have shown that the tool damaging is different depending on the position of the die tool in the working area of the press. Therefore, there is a potential to increase the tool service life by means of optimization of the elastic line of a press table during process loading or through proper positioning of a die in the working area of an open press.

2. The conducted experiments and the calculations have proved that it is possible to develop an engineering technique for estimation of the life of cold sheet metal stamping tools.

3. The investigation of the magnetic properties of the hot forging dies material has shown the following: the coercive force increases in the die working cavity areas which are preheated to the recommended temperatures (200–300 ºC), but which are not subject to significant mechanical and thermal loading during operation. The coercive force decreases in the die working cavity areas which are most loaded and heated. This decrease can be explained by the reduction in the length of grain boundaries due to the increase in grain size during heating, as well as by the increased efficiency of healing of the crystal lattice defects due to increased diffusion of atoms.

4. All the investigations conducted have shown that the coercive force increases during mechanical processing due to accumulation of the crystal lattice defects in the surface layer of the material.

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