P. FAJFAR, M. FAZARINC, B. ŽUŽEK, M. TERČELJ

ISSN 0543-5846
METABK 51 (4) 453-456 (2012)
UDC – UDK 669.1:620.17=111

IMPLEMENTATION OF NEWLY DEVELOPED TESTS WITH HEATED AND INTERNALLY COOLED TOOL STEEL SAMPLES FOR DIFFERENT APPLICATIONS

Received – Prispjelo: 2012-01-10
Accepted – Prihvaćeno: 2012-04-10
Original Scientific Paper – Izvorni znanstveni rad

In this study two new tests were developed, i.e., with continuous internal water cooling as well as discontinuous internal water and air cooling. It was proved that the first type of testing is appropriate for simulating the time course of the temperature at a selected depth of a thermally loaded, hot-working die surface layer, i.e., the temperature field on the die surface layer. The second type of testing is appropriate for a study of the thermal fatigue resistance of a tool material.

Key words: diss/continuous internal cooling, tool steels, thermal fatigue, microhardness profile.

Primjena novo razvijenih testova sa grijanjem i unutarnjim hlađenjem uzoraka od alatnog čelika za različite primjene. U ovom istraživanju razvijeni su dva nova testa, tj. test sa kontinuiranom unutarnjim vodenim hlađenjem, kao i test sa diskontinuiranom unutarnjim vodenim i zračnim hlađenjem. Dokazano je da je prvi tip ispitivanja primjeran za simulaciju vremenske raspodjele temperature na odabranoj dubini termalno opterećene površine alata za vruću preradu. Druga vrsta ispitivanja je prikladno za proučavanje otpora termalnog zamora alatnog materijala.

Ključne riječi: ne/kontinuirano unutarnje hlađenje, alatni čelici, termalni zamor, mikrotvrdoća profila.

INTRODUCTION

Hot-working dies are subjected to high thermal, mechanical, tribological and chemical loadings. The cyclic temperature loading as the main load on the die surface layer leads to softening and consequently to a process of wear and thermal cracking [1-9].

An accurate determination of the temperature field on the die surface layer during hot working is still the subject of many investigations [10-11]. An assessment of the thermal loading of an industrial die surface can be assessed using different finite-element codes or finite-difference codes, where the selection of a real value for HTC is usually a difficult task. A direct measurement of the temperature on massive industrial hot working dies with an embedded thermocouple is usually very demanding (in some cases this is also not possible) and expensive, and the accuracy of the measured values is always questionable. Knowledge about the temperature field on the die surface is desired since this is utilized for the selection of appropriate parameters during die-steel processing, the parameters for die surface coatings, the nitriding parameters, etc., aimed at reducing the wear as well as the growth of cracks on the die surface [10-14].

The Gleeble 1500D thermo-mechanical simulator has excellent computer control for the temperature on tested samples as well as the movement of the working jaws. For thermal fatigue testing on the Gleeble 1500D a specimen with a notch but without additional cooling is recommended [14]. It is assumed that the temperature change in the notch is rapid, which leads to the nucleation of cracks and their growth. Since the temperature fields in such testing usually differ from those encountered in industrial applications the direct transfer of the obtained laboratory results to practice is limited. Thus, the above mentioned abilities of Gleeble 1500D enable the development of new tests aimed at a specific application, which would better match the various thermo-mechanical conditions to which metallic materials in their applications are subjected [7-14].

In this contribution, the possibility of applying newly developed tests with computer-controlled heating and internal cooling of the specimen for improving the assessment of temperature on the hot-working die surface layer and for an assessment of the thermal fatigue resistance has been studied.

MATERIALS AND METHODS

Applied specimens and materials

Through the specimen (Figure 1) a hole with 4 mm in diameter was drilled in the axial direction that enables cooling of the specimen with a stream of water or air. A thermocouple (TC) of type K to control the ex-

P. Fajfar, M. Fazarinc, B. Žužek, M. Terčelj, Department of Materials and Metallurgy, University of Ljubljana, Ljubljana, Slovenia

periment was mounted in the middle of the reduced part of the specimen. Thus, the Gleeble 1500D, in addition to a computer-controlled temperature during heating of the sample, and, due to its internal water cooling, also allows the computer-controlled rapid decrease of its temperature. Two modes of testing, i.e., test with heating and simultaneously continuous internal cooling (test mode 1) as well as discontinuous cooling of samples (test mode 2), respectively, were carried out on the Gleeble 1500D.

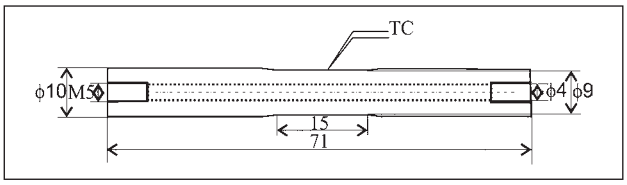

Figure 1 Shape of the specimen

Since the surface layer of each hot-working die (casting, forging, etc.) exhibits a decrease of the microhardness after their service time, it is assumed that on the base of the obtained microhardness profile an improved assessment of the temperature field on the die surface layer during its service time using test mode 1 can be carried out.

The samples for test mode 1 were made from H11 tool steel with the following chemical composition: C 0,35 %, Cr 5,05 %, Si 0,85 %, Mn 0,32 %, Mo 1,37 %, V 0,38% and Fe balance. They were austenitized at 1010 °C for 30 min and quenched in vacuum. The first tempering was at a temperature of 550 °C for 120 min, while the second tempering was at a temperature of 590 °C for 120 min. The microstructure consists of tempered martensite and precipitated carbides. The achieved hardness was 520 HV0.1. The samples for test mode 2 were machined from an indefinite chill iron roll CIN-N-80 with the following chemical composition: C 3,15 %, Ni 4,50 %, Cr 1,77 %, Si 0,92 %, Mn 0,89 %, Mo 0,37 % and Fe balance. The initial microstructure of the outer shell of the indefinite chill iron consists of a matrix of dendrite grains from bainite, martensite, ledeburite and some free graphite.

Cyclic heating and continuous internal cooling of the specimens (test mode 1)

Cyclic heating and cooling on the hot-working die surface layer leads to a decrease of the microhardness, on the tested specimen as well as to the occurrence of cracks. For a test with a continuous internal cooling time the course of the temperature for each selected depth on the hot-working die surface layer can be simulated. This will lead to a decrease of the microhardness on the tested samples that can also correspond to a decrease of the microhardness for a selected depth on the hot-working die surface layer. The agreement between the obtained microhardness profile on the die surface and the measured values on the tested specimens subjected to assumed thermal loads for each of the selected depths on the die surface layer will serve for the accuracy of the assumed temperature field on die surface layer during its service time. The test cycle can be repeated until sufficient agreement between the mentioned values for the microhardness is achieved, i.e., in the case of an accurate determination of the temperature field. Figure 2 shows the microhardness profile on a laboratory hot-forging die surface layer that was obtained after 1 250 forging cycles and the measured values on heated and internally cooled specimens after

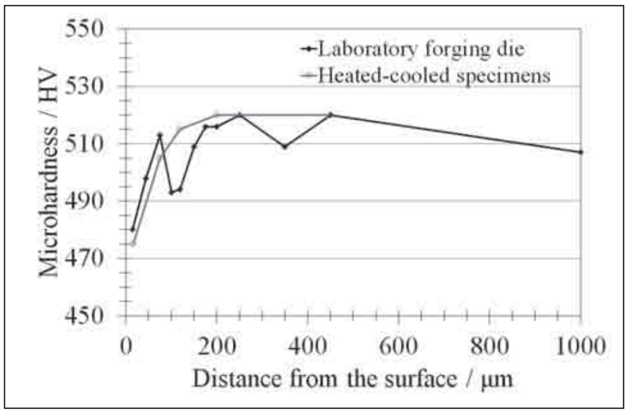

Figure 2 Microhardness profiles

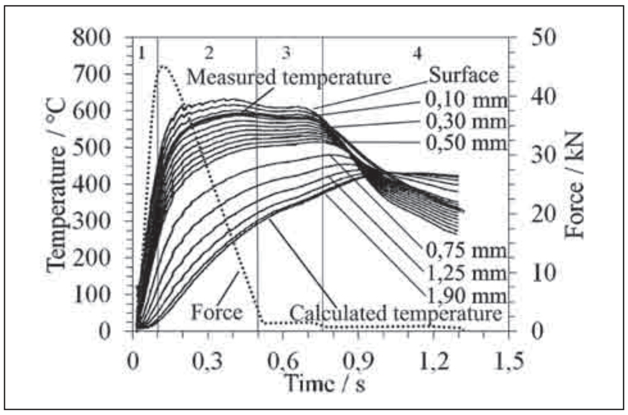

Figure 3 Measured and calculated time course of temperature for the hot forging

1 250 cycles during a simulation of the temperature profile for selected depths.

Furthermore, on the basis of the agreement between the values of the microhardness of this profile with the obtained values of the microhardness on the tested samples, the possibility of the application of this test for an improved assessment of the temperature field on the hot-working surface of the industrial dies during their service time was studied. Typical measured values of temperature at approximately 0,15 mm below the die surface during laboratory hot forging and calculated temperature field on die surface layer which procedure is described in [10] are given in Figure 3. Characteristic points on the measured curve (Figure 3) regarding the tool-workpiece position represent: 1–deformation, 2–decreasing of force, 3–slight contact, 4–no contact. The contact time was 0,5 s and the specimen temperature was 950 °C. Here we should emphasize that during embedding of the thermocouple close to the surface of the industrial die it is not entirely clear to which depth belong the measured values of the temperature since the large size of the TC hot point as well as the response time of the TC influence the accuracy of the measured values of the temperature. By computer-controlled cyclic heating and continuous internal cooling of the specimens the temperature time courses for each selected depth on the die surface layer (Figure 3) can be simulated. On the basis of the obtained values of the microhardness on the tested samples and from their comparison with the microhardness profile on the surface layer of a real die, a more accurate assessment of the temperature field can be carried out. The procedure with test mode 1 for all the selected depths on the die surface layer can be repeated until the applied temperature courses lead to sufficient agreement between the mentioned microhardness profiles.

Additionally tests at temperatures of 650 °C, 750 °C and 850 °C for various numbers of cycles, i.e., 500, 1 000 and 3 000, were carried out. These tests served for the determination of area on specimen cross-section which is subjected to prescribed computer guided time courses and where measurements of microhardness were carried out.

Cyclic heating and discontinuous cooling of the specimen (test mode 2)

A higher temperature gradient on the tested surface is achieved during this type of testing. It seems that this test will be appropriate for a study of the thermal fatigue resistance of steels aimed at the production of hot-rolling rolls. Discontinuous cooling of the internal specimen surface with water and air after heating simulates the cooling of the roll surface.

In this batch of tests the specimens were tested under similar conditions found on the surface of rolls during the hot-rolling process. The specimens were heated to four different temperatures, 400 °C, 500 °C, 600 °C and 700 °C. After the specimens attained the test temperature, they were computer-controlled internally cooled with water which was then ejected by air. The experiments were interrupted at 500 and 1 000 cycles; the duration of each temperature cycle was 4,8 s.

RESULTS AND DISCUSSION

Continuous internal cooling of the specimen

The measured values for the microhardness on the specimen radial cross-sections after 500, 1 000 and 3 000 cycles and for the test temperature of 750 °C reveal that these values decrease from the cooled inner side to the outer side of the specimen, where considerably higher temperatures prevail. But at a distance of approximately 0,5 mm from outer surface of the specimen about the same level of decrease of the microhardness for each number of the cycle and the testing temperature was obtained. Consequently, within the mentioned depth on the specimen surface layer a measurement of the microhardness should be carried out. During testing at the maximum temperature of 850 °C this value amounts to approximately 0,25 mm, while during testing at a temperature of 650 °C this value amounts to 0,75 mm. Furthermore, the micro-cracks also appeared only on the inner surface of the specimen at the highest temperature (850 °C) and the largest number of thermal cycles (3 000). At the outer surface of the specimen only a few cracks appeared. More cracks were found on the inner surface in intervals of 20 μm to 50 μm and their average length of 6 μm. At lower temperatures, the cracks did not appear.

The measured values of the microhardness on a specimen for a simulation of the temperature time course for selected depths on the die surface (Figure 3) are given in Figure 2. Good agreement between the measured microhardness profiles on the die surface layer with those obtained on tested samples was achieved. As mentioned in the case of the measured lower values of the microhardness on the tested samples higher temperatures for the next test mode 1 should be applied until sufficient agreement is achieved. Thus, applying test mode 1 is appropriate for a determination of the temperature field on the die surface layer and less appropriate for thermal fatigue testing.

Discontinuous internal cooling of the specimen

Thermal cycling causes the appearance of cracks on the surface of the specimen. Carbides represent the main source of crack initiation due to the different thermal coefficients of expansion. At elevated temperatures, crack propagation is enhanced by the formation of carbides and oxides. Because the volume of the oxide is

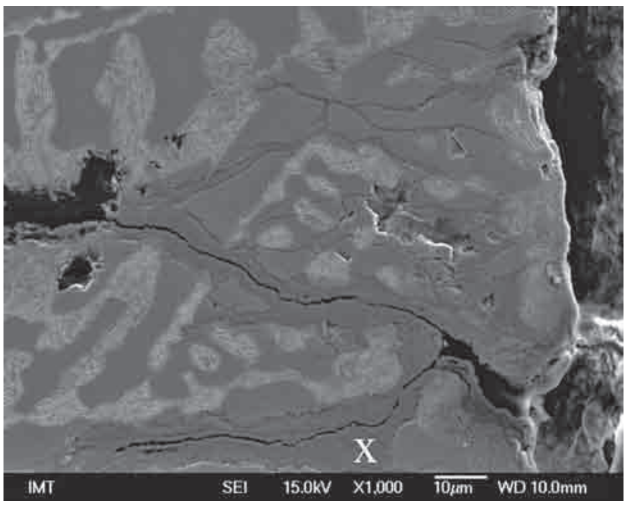

Figure 4 SEM image of cracks after 500 cycles at the test temperature of 700 °C

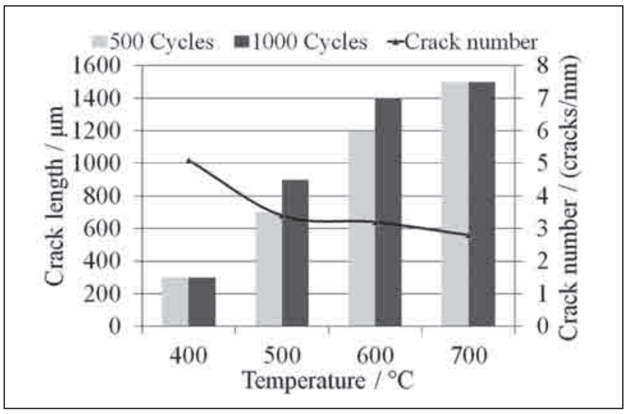

Figure 5 Maximum lengths of the cracks and the crack number for 1000 cycles

greater than that of the base metal, the oxides cause the formation of wedge-shaped cracks (Figure 4). The chemical composition of the oxide (x) is O 29,36 %, Cr 2,1 %, Ni 1,48 %, Mn 0,94 %, Si 0,43 % and Fe balance. The crack propagation is trans-granular and intergranular.

Thermal fatigue cracks appear in all the specimens after testing. In the 2,5-mm-thick wall of the specimens the cracks reached a depth of 200 µm to 1 500 µm. The maximum lengths of the cracks are shown in Figure 5. They are larger at the temperatures of 500 °C and 600 °C in the case of 1 000 cycles for about 200 µm in comparison with 500 cycles. At the temperatures of 400 °C and 700 °C the number of cycles has no influence on the lengths of the cracks. With a higher thermal fatigue temperature and a greater number of cycles the cracks becomes wider and deeper, but they appear in a smaller number. At a temperature of 400 °C, there were on average 5,1 cracks per millimeter of surface length and at the temperature 700 °C, the number of cracks was reduced to 2,8 cracks per millimeter (Figure 5).

CONCLUSIONS

In this research work the implementation possibilities for the results obtained on specimens subjected to computer-controlled heating and internal cooling simultaneously, was studied. Two types of tests were carried out on a Gleeble 1500D. The following conclusions can be drawn:

- Tests with continuous internal cooling of the specimen are appropriate for the simulation of the temperature time course for selected depths on the hot-working die surface, i.e., for an improved assessment of the temperature field on the die surface layer during its hot working. Very good agreement between the measured microhardness profile on the die surface layer of the laboratory hot-forging tool and the measured values of the specimens subjected to same temperature loading was obtained.
- Testing with discontinuous cooling is appropriate for thermal fatigue testing since the obtained lengths of the cracks on the internal surface for indefinite chill iron roll (CIN-N-80) were up to 1500 µm after 1000 cycles. The cracks for the tested indefinite chill iron roll (CIN-N-80) appear on the cooled surface only, usually on the carbides' phase boundaries. With an increase in the number of cycles deeper and wider cracks occur, while with an increase of the testing temperature the number of cracks decreases, but their length increases. The crack propagation is enhanced by oxidation.

REFERENCES

[1] A. Persson, S. Hogmark, J. Bergström, Int. Journal of Fatigue, 26 (2004) 1095-1107.
[2] D. Klobčar, J. Tušek, B. Taljat, Mat. Science and Engineering: A, 472 (2008) 198–207.
[3] T. Pepelnjak, B. Barišič, J. of Mater. Process. Technol., 186 (2007) 111-119.
[4] T. Pepelnjak, G. Gantar, K. Kuzman, J. Mater. Process. Technol., 115 (2001) 122-126.
[5] D. Klobčar, J. Tušek, Computational Material Science, 43 (2008) 11, 47–54.
[6] M. Petrič, J. Medved, P. Mrvar, Metalurgija, 50 (2011) 2, 127-131.
[7] A. Persson, S. Hogmark, J. Bergström, J. of Mater. Process. Technol., 152 (2004) 228-236.
[8] A. Persson, J. Bergström, C. Burman, S. Hogmark, Surface and Coatings Technology, 146-147 (2001) 42-47.
[9] L. Lavtar, T. Muhič, G. Kugler, M. Terčelj, Eng. Fail. Analysis, 18 (2011) 4, 1143-1152.
[10] M. Terčelj, R. Turk, M. Knap, Applied Thermal Engineering, 23 (2003) 2, 113-125.
[11] J.O. Aweda, M.B. Adeyemi (HTC), J of Mat. Process. Technol., 209 (2009) 3, 1477-1483.
[12] S. Amiable, S. Chapuliot, A. Constantinescu, A. Fissolo, Int. J. of Fatigue, 28 (2006) 692-706.
[13] M. Fazarinc, R. Turk, G. Kugler, P. Mrvar, M. Terčelj, RMZ–Materials and Geoenvironment, 54 (2007) 1, 33-48.
[14] L. A. DobrzańskI, K. Golombek, , J. Kopač, M. Soković, J. Mater. Process. Technol., 157-158 (2004) 304-311.
[15] Gleeble 1500 Operations Manual, Duffers Scientific, Inc. 1989.

Note: The responsible translator for English language is Paul McGuiness.