MECHANIKA TEORETYCZNA
I STOSOWANA
Journal of Theoretical
and Applied Mechanics
1, 32, 1994

EFFECT OF SERVICE CONDITIONS UPON THE PROCESSES OF METAL MOULD FATIGUE FRACTURE

MAREK CIEŚLA

TADEUSZ LAMBER

JERZY OKRAJNI

MAREK PLAZA

Chair of Mechanics and Plastic Working Technology
Silesian Technical University

The paper presents some results of investigations into the crack nucleation and development due to thermal-mechanical fatigue of metallic moulds. A practical example have been taken to discuss a concept of the fatigue life prediction with an application of material simulation tests and modelling approach to a subject.

1. Introduction

Metallic moulds such as cast-iron ones are commonly used in metallurgical industry. These moulds are exposed to cyclic temperature fields due to the contact with liquid metal and cooling of the mould working surface. Heat influx in these conditions causes large temperature gradients what results in stress of levels sometimes exceeding locally the material strength leading to mould surface cracking. At the same time corrosion and erosion effects can be also noticed. Moreover, being exposed to prolonged influence of high temperatures, the material becomes structurally unstable (cf Gundlach, 1985; Okrajni, 1988). All the above mentioned factors determine the moulds durability.

Prediction of safe and failure-free life of technical devices is one of important issues in the industrial practice and, hence, the designers have to apply an appropriate methodology to the material feature selection. It is necessary, therefore, to use the durability criteria corresponding with the given working conditions, and models simulating the subjects' behaviour.

This work concentrates upon the problem of mould durability, associated with the material structure features and the microstructure transformations caused mainly by elevated and fluctuating temperature. Taking as an example some selected devices a methodology of subject modelling for evaluation of physical fields has been discussed here.

2. Selection of criteria for material life-time evaluation

To discuss a way to select an appropriate criterion for material assessment under the given conditions a model approach to heat transfer phenomena were applied, taking as an example the axially-symmetrical case. The course of temperature, stress and strain variations in a thick-walled tube was analysed. An intensive heat exchange at the inner surface was assumed with the heat transfer coefficient $h = 0.27$ 1/m, and much less intensive exchange at the outer surface with $h = 0.004$ 1/m. These parameters were to reflect the conditions possibly close to those typical for metal mould surfaces exposed inside to liquid metal impact and to free air flow, outside.

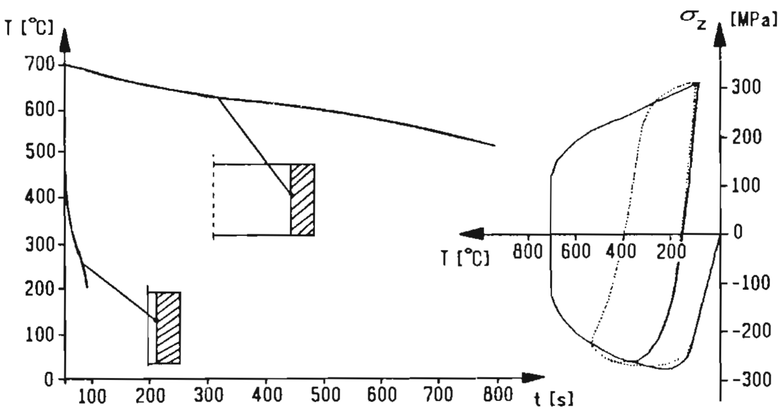

Fig. 1. Time-temperature profiles and axial stress/temperature function at the inner surface of a thick-walled tube exposed to cyclic heating

The elastoplastic model of material with exponential course of hardening was assumed, and temperature impact upon the elastic limit and hardening was taken into consideration. The temperature field was determined with the method of finite differences while the finite elements method was used to evaluation of time-variable stress and strain fields. Fig.1 shows the calculated profiles of temperature change with time, and the corresponding axial stress characteristics as a function of temperature at the tube internal surface. These calculations were carried out for a selected tube wall thickness and for two different thickness/inner radius ratios.

In the diagrams a significant effect of the inner radius value upon the course of temperature changes and the thermal-mechanical fatigue characteristics can be observed. Length of the inner radius is – in the case of metal moulds – closely related to the casting size. Therefore, as far as large castings are concerned, the important factor affecting the life-time is the prolonged high temperature exposure. On the other hand, for small castings the crucial role can be attributed to thermal-mechanical fatigue phenomena. These two cases are usually being considered separately allowing for the practical ability to perform the laboratory tests. However, in real terms of industrial practice both thermal-mechanical fatigue phenomena and the temperature-controlled microstructure changes take place simultaneously and they affect each other. Therefore, the tests of structure stability and thermal-mechanical fatigue, being applied to evaluation of the metallic mould materials, should be thought of as boundary cases.

This is why the topic of prediction of the material behaviour, including the life-time, cannot be considered properly taking no account of the subject of the material use.

Hence, the methodology of fatigue life time prediction of subjects of a given form and dimensions which work at the assumed service conditions covers three areas (cf Okrajni, 1988; Kocańda S. and Kocańda A., 1989; Weiss and Pineau, 1992; Lamber et al., 1992):

1. Simulation of the material's behaviour at the laboratory conditions
2. Modelling of an subject with the continuum mechanics approach
3. Modelling of microstructural processes of crack nucleation and development.

3. Practical example

To demonstrate some selected elements of the methodology an example of metal mould for fire-bar casting has been taken. For a gray cast-iron mould

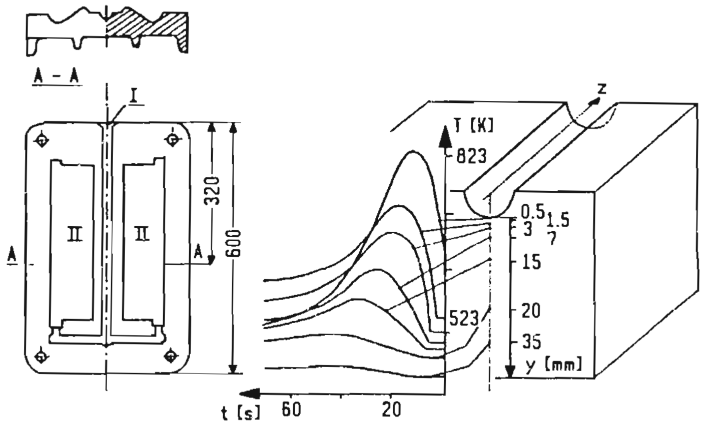

Fig. 2. A mould for fire-bar casting and measured temperature changes with time at points located in various distances from the mould's gate assembly surface

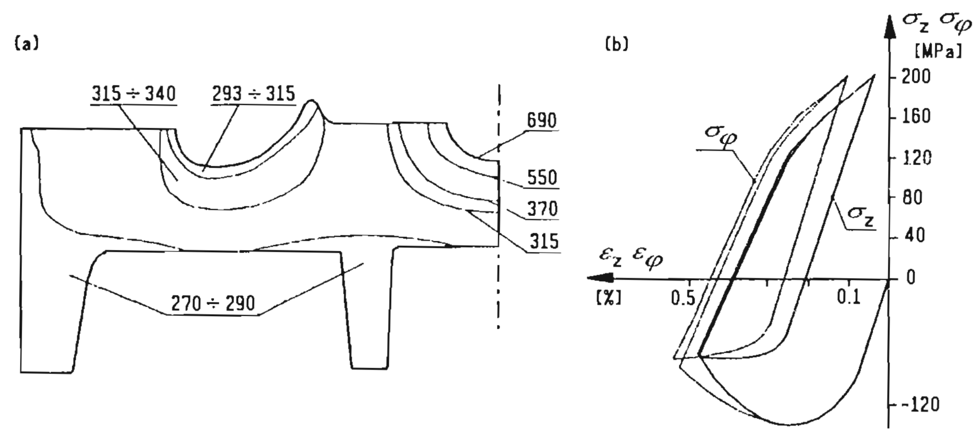

Fig. 3. (a) temperature distribution over the mould cross-section calculated with the finite differences method, $t = 10$ s; (b) relationship profile between the stress and strain components at the gate assembly surface calculated with the finite elements method

the service temperature measurements were taken (Fig.2). In this way the areas of the most intensive fatigue process were indicated. Using the method of finite differences the distribution of temperature in the mould cross-section were evaluated and the relationship between stresses and strains at the moulds gate assembly was determined (Fig.3).

3.1. Investigations of thermal-mechanical fatigue

At the laboratory environment some tests of selected cast-iron grades were carried out with simulation of temperature changes at the gate assembly surface (Chladek et al., 1984), and the results obtained were quite similar to these measured at the subject (Fig.4). Moreover, fatigue diagrams were worked out. A relationship between the life-time (number of cycles to failure) and stereological features of graphite was found (Lamber et al., 1991).

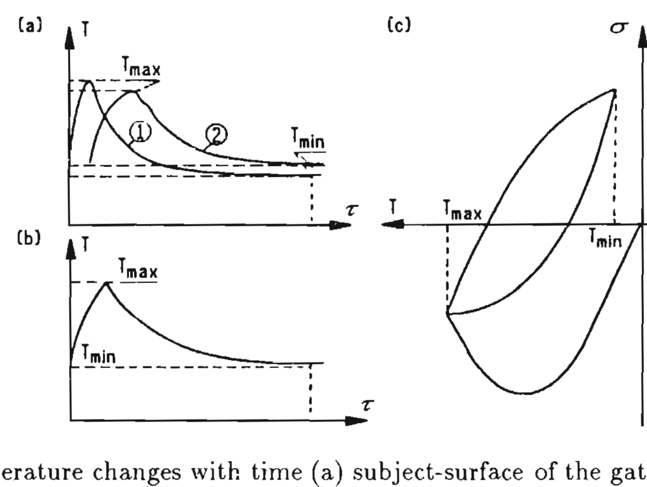

Fig. 4. Temperature changes with time (a) subject-surface of the gate assembly and the mould cavity; (b) a specimen for thermal-mechanical tests; (c) stress/temperature diagramme of a specimen

3.2. Studies of the microstructure stability

Data concerning the microstructure stability of cast-iron at elevated temperatures can be obtained by long-time annealing with subsequent metallographic observations and hardness tests. In this way the processes of cementite

Fig. 5. Microstructure of gray cast-iron with 0.12isothermal annealing (magnification 250×); (a) time $t = 50$ h, temperature $T = 500°C$; (b) time $t = 50$ h, temperature $T = 600°C$, (c) microstructure of surface layer (mould cavity surface) of gray cast-iron metallic mould

decomposition and internal oxidation can be studied. Some typical microstructure changes of selected gray cast-iron grades after annealing have been shown in Fig.5. The results of hardness tests of selected cast-iron grades have been collected in diagrams (Fig.6). Measurements of mass increase with time of a specimen exposed to high temperature in air have been applied to investigate the kinetics of cast-iron oxidation process and given in Fig.6.

Table 1. Chemical composition of the investigated low-alloy cast-iron

Gr	[%]											S_c
	C	Si	Mn	P	S	Cu	Sn	Sb	Cr	Mo	Ni	
1	3.1	1.85	0.79	0.06	0.014	-	-	-	0.04	0.03	-	0.83
2	3.1	1.98	0.68	0.05	0.015	0.8	-	-	0.08	0.04	-	0.84
3	3.0	1.90	0.67	0.05	0.015	-	-	0.11	0.08	0.04	-	0.82
4	3.0	1.85	0.67	0.05	0.015	-	0.12	-	0.15	0.03	-	0.82
5	2.9	2.20	0.70	0.06	0.010	0.7	-	-	0.20	0.30	0.5	0.82
6	3.0	1.95	0.07	0.06	0.014	-	-	-	0.60	-	-	0.82

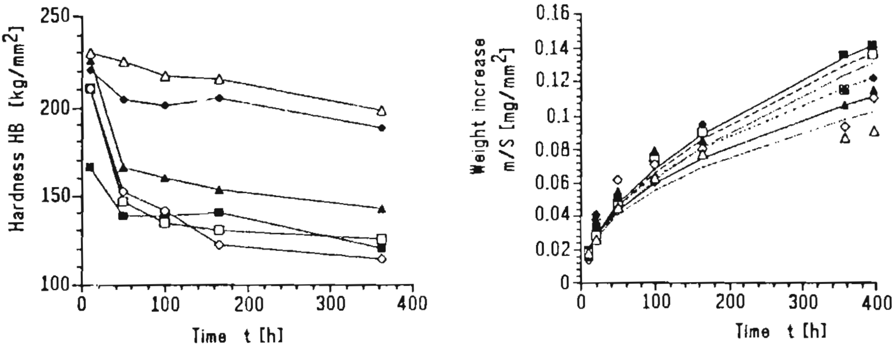

Fig. 6. Results of hardness tests and oxidation trials of gray cast-iron with various content of alloying components. Details are given in Table 1

4. Conclusions

When taking into consideration the thermal-mechanical fatigue phenomena excluding, however, such factors as the effect of long-term high temperature exposure, the estimation of the material life-time can be based upon a comparison of criterial parameters describing the course of cyclic elastic-plastic deformation and the corresponding characteristics of the material life-time. Most often than these parameters the equivalent range of total or plastic strain is taken (cf Brown, 1973; Chladek et al., 1984; Kocańda S. and Kocańda A., 1989; Weiss and Pineau, 1992). In this way the life-time of moulds can be estimated but only in the case of castings mass relatively small in comparison with the mould mass. When the effect of prolonged service time is becoming more and more significant for the microstructure-controlled changes of the material properties, then such an estimation makes it possible to predetermine the moment of the first crack appearance. Development of these cracks will take place at the conditions of microstructure changes in consecutive load cycles with simultaneous impact of surface oxidation phenomena. This increases the crack lengths and makes the oxidized layer of the mould cavity, gate assembly and at the crack inner surface to spall. As a result, the geometric surface features change. In this case as a criterion for the decay of the service properties the mould surface state can be taken that affects the casting quality which is particularly important for precision, complex shape castings.

The number of cycles to failure calculated upon the basis of results of thermal-mechanical fatigue tests in the case of the given practical example has been estimated at approx. 15% of the number of cycles which puts the mould out of service. Moreover, in the course of the mould use cracks were observed to appear over the inner cavity and gate assembly surface, and these cracks developed later as a results of the scale spalling. The microstructure of the surface layers changed considerably, too (Fig.5c). These were the main phenomena that control the state of working surface of the mould, and, therefore, that determine its life-time.

Because of mutual interactions between the surface damage processes existance the discussed results can be so far hardly used to precise determination of safe life-time of the subject of the analysis. However, the intensity of each particular component of damage processes in various materials can be estimated in this way. The data obtained out of the analysis have been practically utilized to proper selection of the cast-iron grade for the moulds.

References

1. BROWN W., MILLER K.J., 1973, Prace Inst. Mech. Eng., London, 187, 745
2. CHLADEK W., LAMBER T., PLAZA M., 1984, *Untersuchungen zur thermischen Ermudung von Kokilen aus GGL mittels servohydraulischer Prufmaschinen,* Neue Hute 29, Jahrgang, Heft 10
3. GUNDLACH R.B., 1985, *Wirkung von Legieren elementen auf die Eigen schaften von Graugus bei h"oheren Temperaturen,* Giesserei-Praxis, 1-2, Berlin
4. KOCAŃDA S., KOCAŃDA A., 1989, *Niskocykliczna wytrzymałość zmęczeniowa metali,* PWN Warszawa
5. LAMBER T., CIEŚLA M., OKRAJNI J., 1991, *Einfluß der quantitativ Bestimmten Graphitkenngroß auf die Lebensdauer von Kokilenguß,* IX Symposium Verformung und Bruch, Magdeburg
6. LAMBER T., OKRAJNI J., PLAZA M., 1992, *Estimation of the Structural Members Low-Cycle Fatigue Durability,* Third International Conference on Low-Cycle Fatigue and Elasto-Plastic Behaviour of Materials, Berlin
7. OKRAJNI J., 1988, *Niskocykliczna trwałość stali żarowytrzymałych w warunkach oddziaływa' n mechanicznych i cieplnych,* ZN Pol.Śl., 32, Gliwice
8. OKRAJNI J., 1991, *Microstructural Aspects of the Low-Cycle Fatigue of Creep-Resisting Steels,* IX Symposium Verformung ud Bruch, Magdeburg
9. WEISS J., PINEAU A., 1992, *Microstructuraly - Based Simulation of Multiaxial Low-Cycle Fatigue Damage of 316L Stainless Steel in Terms of the Behaviour of a crack population,* Third International Conference on Low-Cycle Fatigue and Elasto-Plastic Behaviour of Materials, Berlin

Wpływ warunków eksploatacji na mikrostrukturalnie determinowane procesy zmęczeniowego pękania form metalowych

Streszczenie

W pracy przedstawiono wyniki badań procesu powstawania i rozwoju pęknięć w warunkach zmęczenia cieplno-mechanicznego form metalowych. Posługując się przykładem technicznym omówiono zagadnienia prognozowania trwałości form metalowych w oparciu o wyniki badań symulacyjnych materiału i modelowe ujęcie obiektu.

Manuscript received October 1, 1993; accepted for print October 14, 1993