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THERMAL FATIGUE OF THE SELECTED TOOL STEEL APPLIED FOR METAL MOULDS ELEMENTS IN DIE CASTING OF METALS

ZMĘCZENIE CIEPLNE WYBRANYCH STALI NARZĘDZIOWYCH STOSOWANYCH NA ELEMENTY FORM METALOWYCH W ODLEWNICTWIE CIŚNIENIOWYM

The work presents the results of research on thermal fatigue resistance of four steel grades used in the production of metal moulds for pressure diecasting. Thermal fatigue tests were performed on an original test bench using the L.F Coffin method – resistance heated samples. The steels additionally contained alloy additives in the following proportions: Cr = 5.0÷5.3%, Mo = 1.30÷3.0%, and V = 0.50÷1.0%. The thermal fatigue was analyzed using the temperature cycle: T_{min} = 200°C; T_{max} = 700÷750°C. The samples endured between few to few dozens of thousands of temperature cycles in the above temperature range. Steel with maximum vanadium content exhibited the highest level of resistance.

Keywords: thermal fatigue, alloy steel, metal moulds, pressure diecasting

W pracy prezentowane są wyniki badań odporności na zmęczenie cieplne czterech gatunków stali stopowych stosowanych na elementy form ciśnieniowych. Badania zmęczenia cieplnego wykonano na oryginalnym stanowisku badawczym stosując metodą L.F. Coffina – oporowe nagrzewanie próbek. Stale zawierają dodatki stopowe w ilości: Cr = 5.0÷5.3%, Mo = 1,30÷3,0% oraz V = 0,50 ÷1,0%. Zmęczenie cieplne badano przy cyklu temperatury: T_{min} = 200°C; T_{max} = 700÷750°C. W opisanym zakresie temperatury próbki wytrzymywały od kilku do kilkunastu tysięcy cykli cieplnych. Największą odporność wykazywała stal z maksymalną zawartością wanadu.

1. Introduction

Pressure casting dies are the most often a very complex structures and their production requires a high labour input. Therefore attempts are undertaken to obtain their long working time, determined by the number of the die mould pouring with liquid metal. Several processes and effects are taking part in the mould wear. Die moulds undergo influences of cyclically changing mechanical and thermal stresses, of abrasive wear effects (casting knocking out), and of corrosion processes accelerated by high temperatures. Relatively high temperatures of near-surface mould layers, being in contact with hot metal, leads – in many cases – to phase transformations of materials, and thus to changes of their mechanical properties. Mould plugs, cores, slides and gate elements operate under the most difficult conditions. External indications of material wearing are micro and – later – macro-cracks occurring on the mould surface, making castings knocking out, without their deformations or other damages, impossible.

The effect of material thermal fatigue plays the most important part in the complex process of wear and tear of metal moulds, made of steel. Under the thermal fatigue name, the process of not isothermal low-cyclic fatigue, during which elastic and hot deformations are accompanied by the maximum temperature, is understood in the scientific literature [1-8]. Such combination of thermal and shock load cycles, causes an occurrence of several specific effects in the thermal fatigue process, changing the state of stress. During the initial period of the cyclic heating the compressive stresses dominate but as the number of heat cycles increases the tensile stresses start to overbalance.

A thermal fatigue resistance is one of the most important property of material used for making metal moulds. Since production costs of metal moulds are high (decrement treatment on automates CNC), it is important to select the proper material. Hot work tool steels are the most often applied for metal moulds (WCL, WCLV, WLV, WWV) containing carbide forming and/or alloying components increasing heat resistance, such as: Cr, W, V, Mo and Co [12, 13, 14]. These steels, after a heat treatment, have the most often the transformed martensite matrix or bainite with carbide precipitates. In dependence of the steel chemical composition and its heat treatment, carbides are of various compositions, shapes, sizes and distributions. They decide, to a large measure, on physical and mechanical properties of steel or cast steel, including thermal fatigue resistance.

Thermal fatigue resistance measurements of a few steel grades, intended for 'hot' works, were performed within this study (in the temperature range: 200 – (700÷750°C).

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2. Author's own studies

2.1. Materials and methodology of thermal fatigue investigations

Hot work tool steels belong to low-alloy steels with additions of carbide-forming elements, mainly: Cr, V, W and elements improving strength at increased temperature: Mo and Co. Four, typical materials, applied in the production of metal moulds for pressure die casting were selected for investigations. Chemical compositions of materials are given in Table 1. They have a similar carbon content (0.35÷0.40%) and a stabilised content of the carbide-forming element, which is chromium (5.0÷5.3%). They differ in the molybdenum content (~1.35% or 3.0%) and in vanadium content maintained at three levels (0.40, 0.60 or 1.0%). This combination of the alloying elements content provides various ability of the heat treatment of individual steels. It also provides different functional properties, including thermal fatigue resistance – the basic property of hot-working materials.

TABLE 1

Chemical composition of investigated steels applied as materials for die moulds elements

Lp.	Nr materials	Chemical composition [%]						
		C	Si	Cr	Mo	V	Mn	S
1	2	3	4	5	6	7	8	9
1	**1**	0,38	1,00	5,30	1,30	0,40	-	
2	**2**	0,37	-	5,00	3,00	0,60		
3	**3**	0,35	0,30	5,00	1,35	0,45	0,35	<0,003
4	**4**	0,40	1,00	5,30	1,40	1,00		

The thermal fatigue resistance is – from one side – a difficult for estimation property and – from the other and in the majority of cases – the most important property of materials used for structures working under conditions of cyclically changing temperatures and stresses. Stresses which are cyclically loading the heated elements are mostly of a thermal character, however they can occur in combination with mechanical stresses. In case of metal moulds used for gravity castings thermal stresses are dominating, while in case of die moulds the thermal and mechanical stresses prevail.

Multiplicity of methods of assessments of the thermal fatigue resistance of metal alloys [1-8] developed in the last several dozen of years, renders difficult the results comparison. In addition, the assessment criteria of this resistance have various dimensions (physical dimensions). In one method: this is the number of cracks occurring after the selected number of thermal cycles, in another: it is the length of micro and macro-cracks and in still other: it is the number of cracks in the selected segment (cracks intensity).

The L. F. Coffin [1] method, in which the sample in a bar shape is resistance heated, was applied in investigations of tool steels. A high intensity current flowing through the sample causes its fast heating. The sample, fixed stiffly in the device holders, relatively well represents thermal stresses of the upper mould layers contacting with liquid metal. Expansions of the upper layers intensively heated by liquid metal are hampered by less heated deeper layers. Similar situations occur in testing the thermal fatigue of a bar sample fixed from both sides in device holders. It is shown in Fig. 1.a. A cyclic heating of the sample – according to the scheme in Fig. 1.b – leads to creation of uniaxial state of stresses and deformations, which can be seen in Fig. 1.c. As the thermal cycles number increases the hysteresis loop in the system: stress – deformation stabilizes, with regard to the range and values of stresses and deformations.

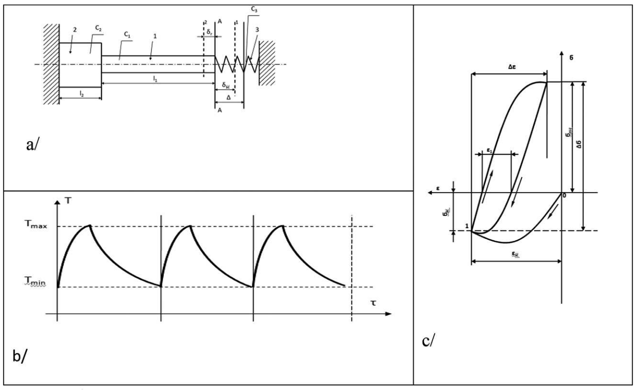


Fig. 1. Model of the thermal stress loading of material in the thermal fatigue process (L.F. Coffin model – bar sample); a – Scheme of the sample heated with hampering the possibility of a free thermal elongation, b – Typical changes of the sample temperature, c – Typical pathways of stresses and deformations of the sample in the first and in successive thermal cycles [2]

Cyclically repeated thermal and stress loading of material leads to its fatigue and to sample breaking (through and through). **The number of thermal cycles, which the sample withstands before breaking is the measure of the tested material thermal fatigue resistance.** Generally, the number of thermal cycles depends on: a kind of material, temperature changes range in each cycle and stress values occurring in the sample during each heating. The level of stresses depends on the temperature range and on the so-called degree of deformation input, the idea of which is presented in Figure 1a. The higher 'stiffness' of the elastic element, the higher degree of the deformation input, the higher stresses during each thermal cycle and the lower number of thermal cycles withstood before the sample breaking.

The actual view of the measuring stand used in the described investigations is seen in Figure 2, and its detailed description is in papers [6-11].

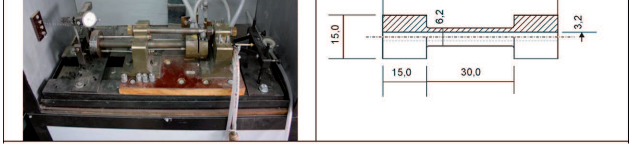


Fig. 2. Measuring stand for testing the thermal fatigue: a) View of the stand; b) Sample dimensions

2.2. Results of investigations

The thermal fatigue resistance of four steels intended for hot working, which chemical compositions are given in Table 1, were measured. Investigations were carried out under constant conditions of the so-called stiffness of the sample fixing system (constant degree of the deformation input). The resistance of these materials was determined at the constant minimum temperature of the cycle (T_{min} = 200°C). Three values of the maximum cycle temperature were applied (T_{max} = 700; 725 and 750°C). The lower temperature of the cycle corresponds with the work temperature of metal moulds for the majority of metal moulds, die moulds and gravity dies. The upper value of the cycle range, which is similar to the mould heating range at casting copper or ferrous alloys, was rather caused by limiting long-lasting experiments. The tested materials sustain, at the described above temperature ranges, a few thousands of cycles, which – when approximately half a minute is needed for one cycle – means that the individual measurement lasts several dozen of hours.

The recorded pathways of temperature and stresses in successive thermal cycles are presented in Figures 3-5. The control thermo-couple, welded to the sample, allows to record temperature changes in the middle of the sample length, that is in places where these changes are the largest. Stresses are calculated on the basis of the constant stiffness of the sample fixing system (schematically marked as a spring in Fig. 1) and on the measured deformations (displacement of bar ends – seen in Fig. 2.a). This displacement is controlled in a contact-less way – by means of the laser sensor and the results are saved in computer in a real time.

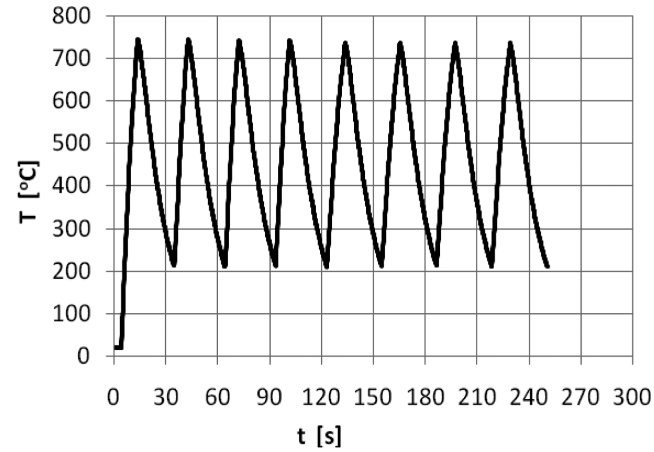


Fig. 3. Typical pathways of sample temperature changes recorded in thermal fatigue investigations of alloyed steels, applied for die moulds

The analysis of the recorded pathways allows to notice a high stability in maintaining temperature ranges of the thermal cycles similar to those, which take place in the mould rhythmically poured with liquid metal. Analysing the states of stress, it can be noticed that already the first cycle causes large plastic deformations. Deformations are caused by the influence of appropriately large compressive stresses, exceeding yield points of the tested material. As the result of these deformations the sample shortening occurs, which – in turn – causes the tensile stresses occurrence during the sample cooling. In the further thermal fatigue process the tensile stresses dominate. They are more disadvantageous for the material durability and become the basic reason of micro and macrocracks formation and of the material continuity gaps.

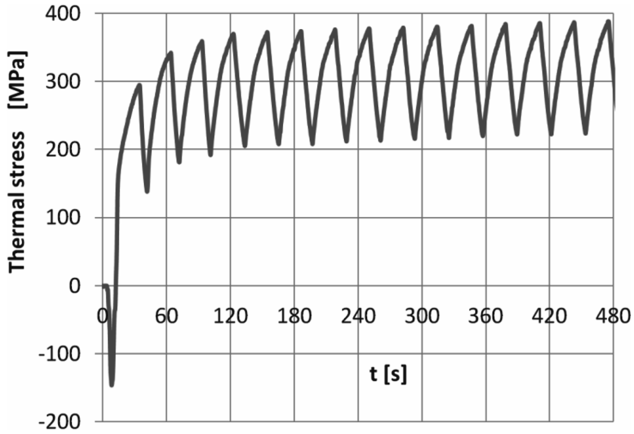


Fig. 4. Changes of thermal stresses in the sample subjected to thermal fatigue investigations (No. 4 steel, temperature range: T_{min} = 200°C, T_{max} = 725°C)

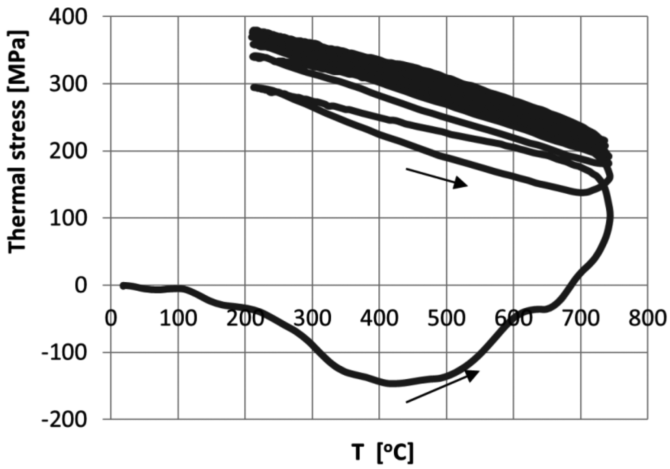


Fig. 5. Relationship between the instantaneous temperature of the heated (and cooled) sample and the thermal stresses occurring in it (No. 4 steel, temperature range: T_{min} = 200°C, T_{max} = 725°C)

The performed investigations of the thermal fatigue under similar thermal and stress conditions allowed to carry out the comparative estimation of the selected alloyed steels, Fig. 6. Out of the examined group of materials the highest resistance characterises chromium – molybdenum – vanadium steel of an increased content of vanadium and silicon (No. 4). A good resistance has also steel of an increased content of silicon and a content of molybdenum and vanadium kept at a middle level.

The influence of the maximum cycle temperature on the alloyed steels thermal fatigue is similar to the one, which is observed for several alloys applied for hot works. It can be described by an exponential equation, which causes that in the logarithmic diagram points are in the straight line. It is shown in Figure 7. Describing the maximum temperature influence by the regression equation allows to forecast the resistance of the investigated material (steel) under different conditions e.g. at lower or higher maximum temperatures of the cycle. This is important, since it enables to forecast the metal moulds durability on the grounds of knowing the temperature, to which the inner mould surface was heated.

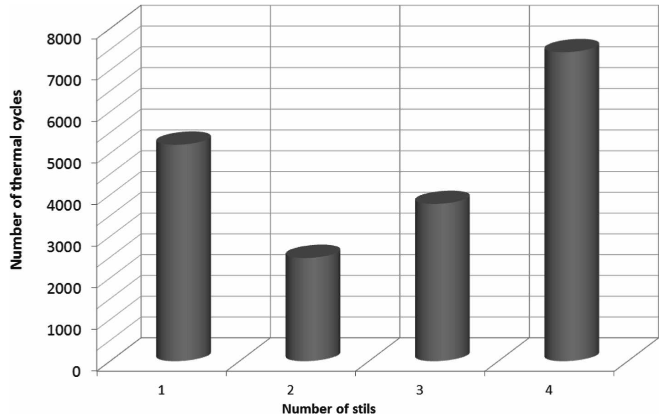


Fig. 6. Thermal fatigue resistance of alloyed steels (Table 1), investigations within the temperature range: T_{min} = 200°C, T_{max} = 725°C

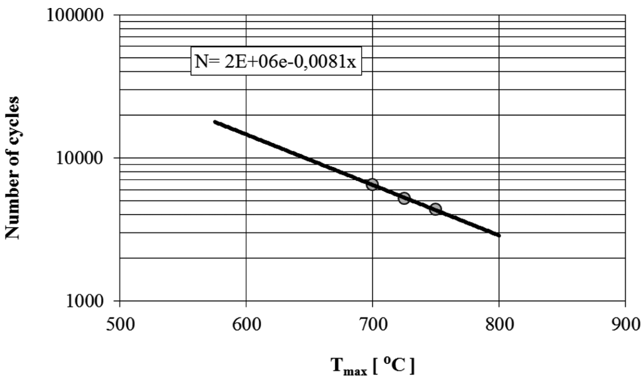


Fig. 7. Typical character of the influence of the maximum temperature of the thermal cycle on the steel thermal fatigue (on the example of No.1 steel)

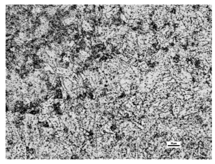
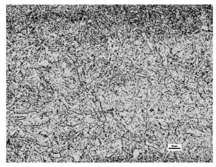
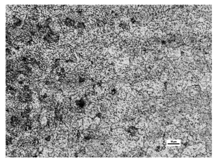
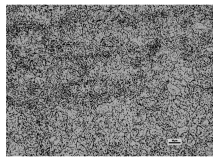
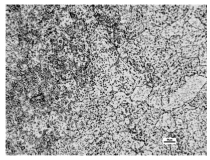
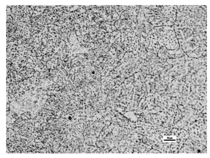
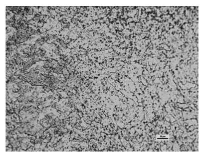
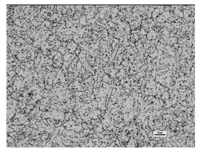
2.3. Microstructure changes in the thermal fatigue process

Comparative investigations of the thermal fatigue resistance were performed for the alloyed steels without quenching and tempering (after soft annealing). Then, the structure was built of alloyed ferrite and spheroidal carbide precipitates, mainly Cr and V carbides. The structure was tested in samples which were previously subjected to a thermal fatigue. The structure was analysed in the zone of the highest heating of samples (their length middle) and in places which were not heavily warmed – in samples heads. In the zone of the maximum sample temperature a grouping and growth of carbide precipitates is observed as well as occurrence of oxides – seen as dark fields on polished sections. The ferritic matrix does not change, in practice. The intensity of this structure rebuilding process is different for each investigated material. The largest changes are observed in No. 1 steel, which contains the smallest amount of alloying elements: molybdenum and vanadium. Oxidizing processes always intensify the structure degradation and contribute to the micro-cracks development.

Generally, within the zone of the highest temperatures and plastic deformations, the formation of clearly visible grain boundaries are seen. Processes of oxidation, movements of structural defects and segregation of fine carbide precipitates occur more intensively on grain boundaries. An extensive analysis of structure transformations requires additional, investigations – being currently under way – which will constitute the separate paper.

TABLE 2

Alloyed steel structure in the state of 'after testing' thermal fatigue

Nr samples	Zone of the highest temperatures – 725°C	Zone not heavily warmed – in samples heads
1		
2		
3		
4		

3. Conclusions

Investigations of four steel grades for 'hot working', applied as a material for die moulds elements indicate quite large differences in their thermal fatigue resistance. Those are steels containing 5.0% of Cr and variable contents of Mo, V and Si. The highest resistance characterises steel of an increased content of vanadium (1.0%) and silicon (1.0%).

Cast steels of compositions given in Table 1 withstand from 2.000 to approximately 10.000 thermal cycles, at the maximum temperature of a cycle from the range: T_{max} = 700÷750°C.

The influence of the maximum cycle temperature can be described by the exponential equation (Fig. 7) and applying the developed equation the number of thermal cycles before occurrence the macro-crack can be forecasted for other parameters of the thermal cycle (lower or higher T_{max}).

The thermal fatigue process at T_{max} = 700÷750°C leads to microstructure changes, to accumulation of carbides on grain boundaries and to matrix oxidations.

REFERENCES

[1] L.F C o f f i n, inni, Trans. Amer. Socjety of Mech. Engineers. TASMA. v. 76, 1954.

[2] P.A. D u l n i e w, P.I. K o t o w, Termiczeskaja ustałost mietałłow, Moskwa, Mašinostrojenie (1980).

[3] A. W e r o ń s k i, Zmęczenie cieplne metali, WNT, Warszawa 1983.

[4] R.B. G u n d l a c h, Giesserei -Praxis **4**, 43-49 (1977).

[5] K. R ö h r i n g, Giesserei -Praxis **23**, 375-392 (1978).

[6] J. Z y c h, Zmęczenie cieplne żeliwa przeznaczonego na formy metalowe, Prace Komisji Metal. Odlew. Metalurgia **38**, 107-116 (1988) PAN Katowice.

[7] J. Z y c h, The Impact of Some Selected Factors on Cast Iron Thermal Fatigue, Zeszyty Naukowe AGH, Metalurgia i Odlewnictwo, Tom 15, 1, 131-145 (1988).

[8] J. Z y c h, D. J ę d r z e j c z y k, Badania odporności na zmęczenie cieplne żeliwa z grafitem wermikularnym, Przegląd Odlewnictwa **6**, 215-218 (1991).

[9] J. Z y c h, Wpływ molibdenu na odporność na zmęczenie cieplne żeliwa szarego z grafitem płatkowym, wermikularnym i sferoidalnym, XX. Konf. Wydziału Odlewnictwa AGH, 93-99 Kraków, 1995.

[10] J. Z y c h, Ocena odporności na zmęczenie cieplne żeliwa szarego, wermikularnego i sferoidalnego, Konferencja Naukowa z Okazji Dnia Odlewnika' 96, Wydział Odlewnictwa AGH, 35-42, 21-22 listopad (1996).

[11] J. Z y c h, J. W r ó b e l, Influence of thermal fatigue of ductile iron GJS(Ni1,5MoCu) – base for producing ADI – on structure and tensile strength, Archives of Foundry Engineering; 2010 vol. 10 spec. iss. 2 s. 177-181. Nogowizin B., Theorie und Praxis der Druckgusses; Schiele &Schön, Berlin 2011.

[12] E. H a b e r l i n g, K. R a s c h e, F. W e n d l, K.-D. W u p p e r, Fortschrichtte und Entwicklungstendenzen auf dem Gebiet der Werkzeugstähle, Thyssen Technische Berichte, Heft 1, 93, 87-95.

[13] L. D o b r z a ń s k i, E. H a j d u c z e k, J. M a r c i n i a k, R. N o w o s i e l s k i, Metaloznawstwo i obróbka cieplna materiałów narzędziowych, WNT, Warszawa 1990.

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