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Effect of microstructural banding in hot-work tool steel on thermal expansion anisotropy

B. Pawłowski*, P. Bała, R. Dziurka, J. Krawczyk
Faculty of Metals Engineering and Industrial Computer Science,
AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding e-mail address: bpawlow@agh.edu.pl

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Properties

ABSTRACT

Purpose: The objective of the present work was to study the effect of the microstructural banding on the thermal anisotropy of hot-work tool steel used for die for aluminium alloy die-casting. In particular, the major purpose of this research was to find possible correlation between geometrically oriented thermal expansion coefficient values and the presence of number of parallel cracks on the working surface of die.

Design/methodology/approach: The studies were performed on the specimens which were cut from the failed prematurely die along the three axes of the coordinate system (X-axe was parallel to the cracks direction). Macroscopic, metallographic, SEM and dilatometric examination were made.

Findings: Surface cracks of die are parallel to the microstructural banding orientation. Differences in the values of thermal expansion coefficient determined along the three axes of the coordinate system probably promote cracks propagation direction.

Research limitations/implications: Studies were performed on the single prematurely failed die for economic reason. This work findings should be compared to the similar examinations results obtained for the another failed dies.

Practical implications: The incorrect microstructural banding orientation of the die core and related differences in the values of thermal expansion coefficient promote crack propagation.

Originality/value: This show the relationship between microstructural banding and the thermal anisotropy of hot-work tool steel used for die for aluminium alloy die-casting.

Keywords: Microstructural banding; Thermal expansion anisotropy; Surface cracks; Die for aluminium die-casting

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1. Introduction

Residual segregation produced during solidifaction may cause the microstructural condition referred to as banding or segregation-induced microstructural banding [1-5]. Microstructural banding is the condition manifested by alternating bands of quite different microstructures aligned parallel to the direction of hot rolling or forging [2]. A widespread type of microstructural banding is alternating layers of proeutectoid ferrite and pearlite [3]. A typical microstructural banding in a hot rolled ferrite-pearlite steel (0.15C-0.16Si-1.07Mn, wt%) is presented in Fig. 1, where 'S', 'T' and 'L' stand for the short transverse, transverse and longitudinal directions respectively [4,5]. A modification of the thermoplastic treatment parameters can significantly limit the banded microstructure formation. However, the heat treatment will not fully liquidate the primary reason, it means the segregation of elements. Further heat treatment operations can lead to the reoccurrence of a ferrite-pearlite banded microstructure [6]. Banded microstructure in forged 18CrNiMo7-6 steel is presented in Fig. 2. The bainitic microstructure in forging cross-section of the 18CrNiMo7-6 steel after heat treatment exhibits very weak banded traces, as it shown in Fig. 3 [6]. As it was reported [7-9], the modification of the microstructure in working surface of hot-work tools steels could be done during surface modifying by means of laser technology which results in refinement of the martensitic structure and hardness increase. The attainment of isotropic microstructures of hot-work tool steels, characterized by homogeneous distribution of fine carbides and segregation free could be made through powder metallurgy route [10]. For martensitic microstructures the only evidence of banding might be small etching differences (often difficult to distinguish) of martensite formed in regions with high and low segregated compositions [3].

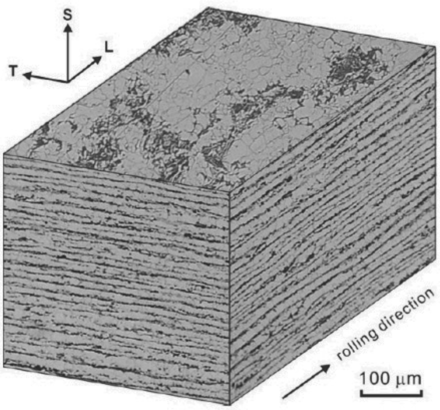


Fig. 1. Optical micrograph showing banded ferrite–pearlite microstructure [4]

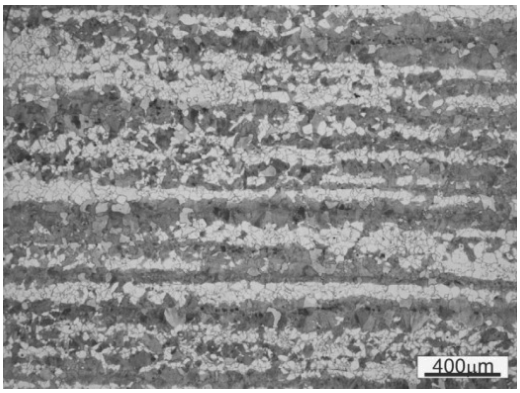


Fig. 2. Microstructure of the hot-forged 18CrNiMo7-6 steel [6]

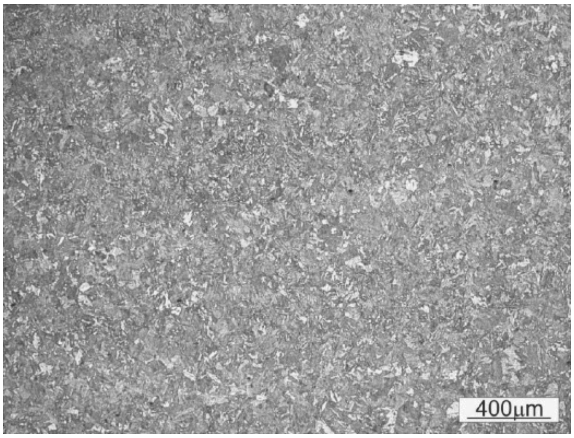


Fig. 3. Microstructure of the forged 18CrNiMo7-6 steel after heat treatment [6]

The present research work have raised from the analysis of the cause of premature cracking of dies for aluminium alloy die-casting [11]. The work [11] revealed that die surface cracks were parallel to the microstructural bands and the improper heat treatment, resulted in fracture toughness of the die five times lower than required for the desired hardness, was the root cause of premature cracking of die. The results of the Charpy impact energy test shown [11] that fracture toughness (impact energy) of the investigated dies was about 5 J for desired hardness 47 HRC against required 27 J (at room temperature for the same hardness level, as it is shown in Fig. 4). The examples of brittle fracture surface images of a Charpy specimens are presented in Fig. 5. Charpy-V specimens were oriented along the three axes of the coordinate system as it is described below and presented in Fig. 7.

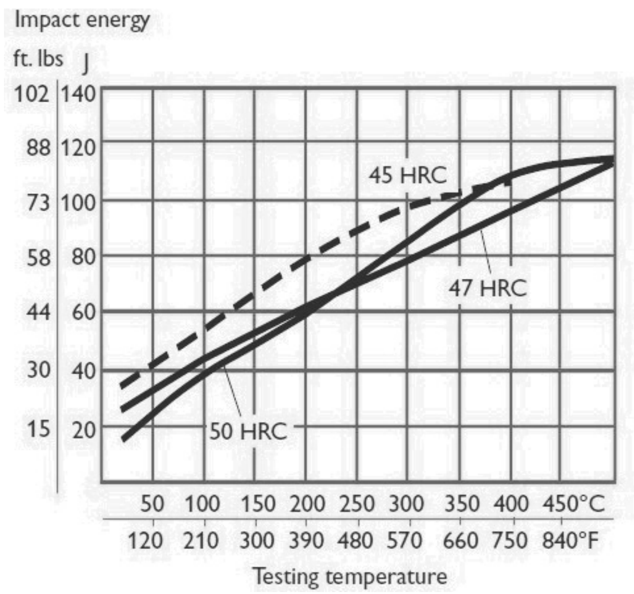


Fig. 4. Charpy V-notch impact toughness of investigated steel versus testing temperature, short transverse direction [12]

a) b) c)

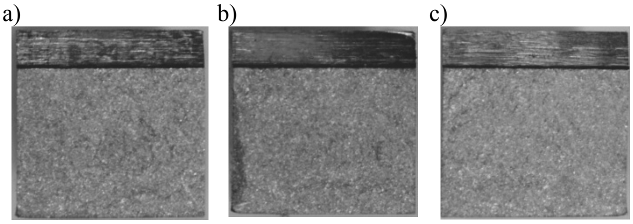


Fig. 5. The brittle fracture surface images of a Charpy specimens, a) XZ plane, b) YZ plane, c) XY plane

The heat treatment of investigated steel is simplified due to the good hardenability but should not be tempered in the range 500-550°C to avoid temper embrittlement [12] contrary to the another hot-work tool H13 steel, for which the optimum heat treatment strategy appears to be tempering in the 525-550°C temperature range to get the best combination of high toughness and high hardness [13]. Regardless of the low toughness, revealed microstructural banding of the die core did not meet the requirements of the manufacturer's design assumptions and could promote crack propagation. Thus, in present work the effect of microstructural banding in hot-work tool steel on the thermal expansion anisotropy was studied.

2. Materials and methods

The parallel cracks, indicated by arrows, on working surface of die are presented in Fig. 6.

The die was made of modern hot-work tool steel with the chemical composition: 0.32% C, 0.22% Si, 0.44% Mn, 4.71% Cr, 2.17% Mo, 0.58% V, and meets the manufacturer requirements [12].

Samples from the die were cut for metallographic and dilatometric investigations. The samples were geometrically oriented along the three axes of the arbitrarily adopted coordinate system, as it is presented in Fig. 7.

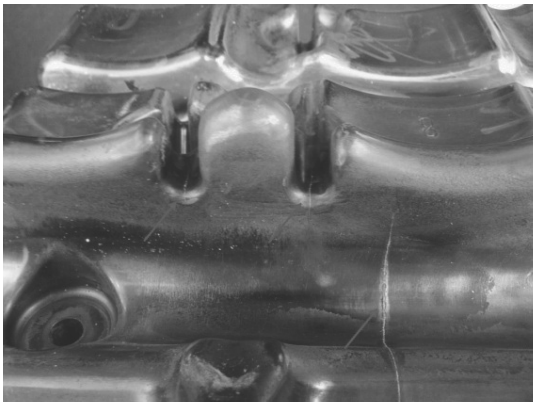
The number of surface cracks, presented in Fig. 6, were parallel to the X-axis; cracked working surface of the die is the XY-plane. For the metallography, macroscopic observation of etched (2% nital) were made and the light microscope Zeiss Axiovert 200MAT was used. As dilatometric test is the simplest way to predict thermal expansion anisotropy of steel, ultra high-resolution dilatometer RITA L78 was used to determine thermal expansion coefficients along to the three axes of the coordinate system. Dilatometric samples (Ø3x10 mm rods) were heated to 600°C (injection temperature of aluminium alloys) at heating rate 0.05°C/s. Thermal expansion coefficients were determined in the temperature ranges 30 - 100°C, 30 - 200°C, 30 - 300°C, 30 - 400°C, 30 - 500°C and 30 - 600°C.

3. Results and discussion

Macroscopic images presenting microstructural banding in investigated die are shown in Figs. 8-10. As it can be seen, bands direction is parallel to the X axis, which is also direction of crack propagation.

In case of samples for metallographic observations using a light microscope, as it was mentioned above, the evidence of microstructural banding manifested in the small but clear etching differences, as it is presented in Figs. 11-13.

a)



b)

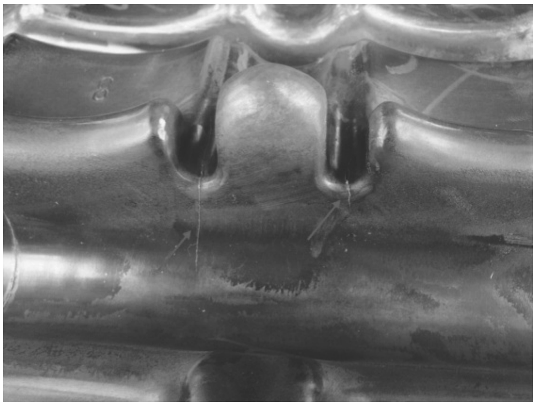


Fig. 6. Working surface of the investigated die, a) three parallel cracks, b) another cracks propagated along the same direction

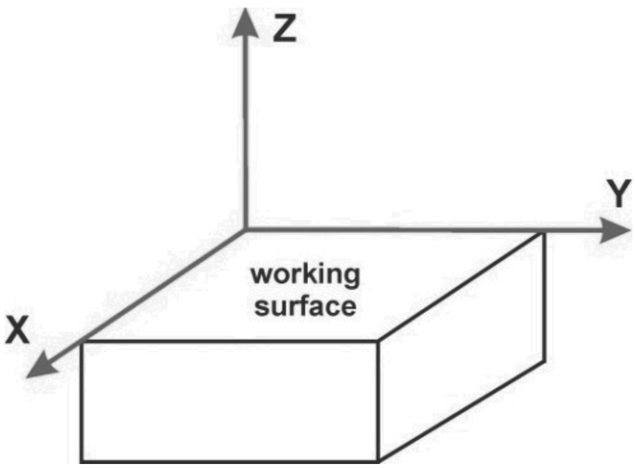


Fig. 7. Adopted coordinate system orientation

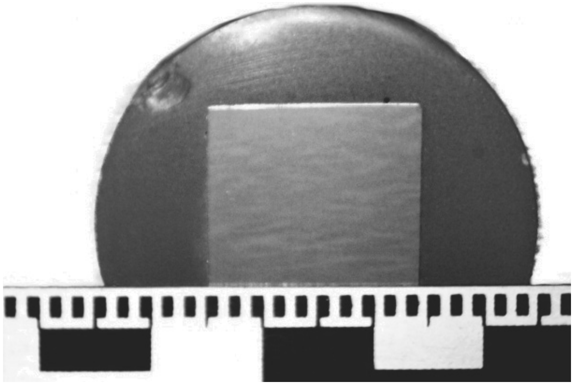


Fig. 8. Macroscopic image of microstructural banding in XZ plane (etched with 2% nital)

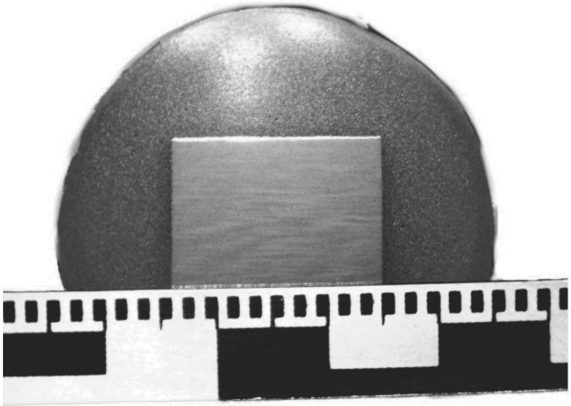


Fig. 9. Macroscopic image of microstructural banding in XY plane (etched with 2% nital)

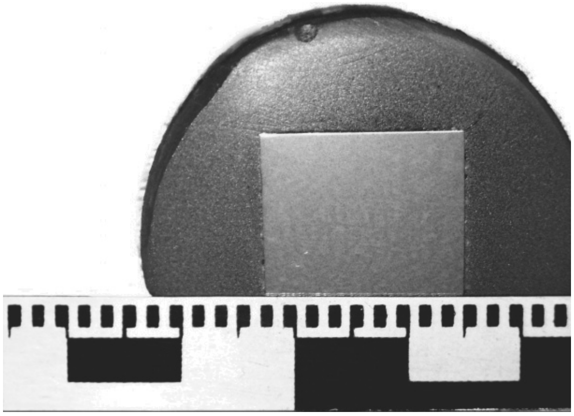


Fig. 10. Macroscopic image of microstructural banding in YZ plane (etched with 2% nital)

Microscopic observations at higher magnification showed appropriate, typical of high-tempered martensite microstructure, as it is shown in Fig. 14.

In the subsurface layer no decarburization regions and wear traces were observed, as it is presented in Fig. 15.

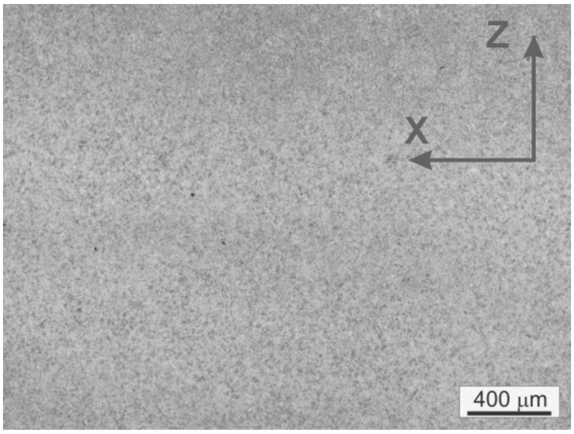


Fig. 11. Microstructure for the XZ plane (etched with 2% nital)

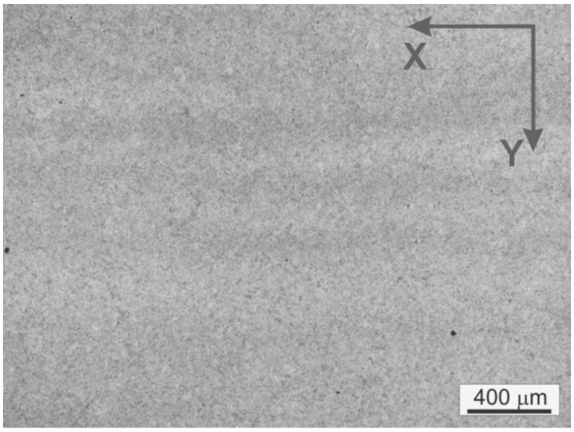


Fig. 12. Microstructure for the XY plane (etched with 2% nital)

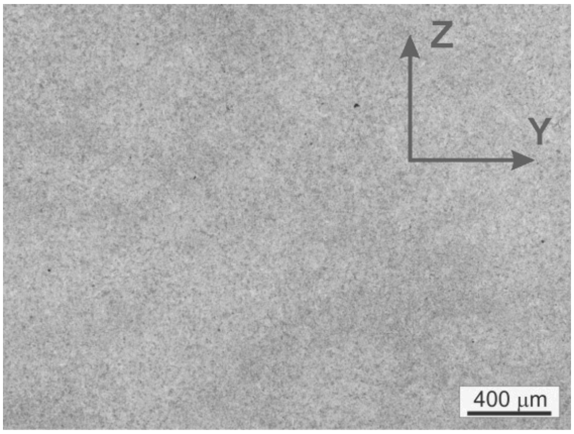


Fig. 13. Microstructure for the YZ plane (etched with 2% nital)

As it was reported in paper [14], cracks observed on the working surface of the die often initiates at identification marks, corners, sharp edges and transitions, as it is presented in Fig. 16.

In present work, microscopic observation of the cooling hole cross-section (Fig. 17) revealed that around the edge of the hole many fine cracks have started.

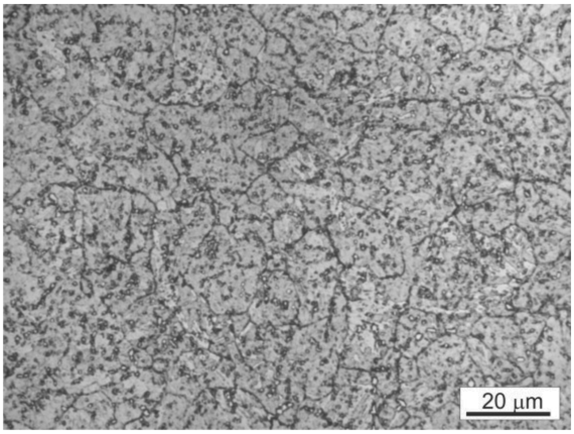


Fig. 14. Tempered martensite microstructure of investigated steel (etched with 2% nital)

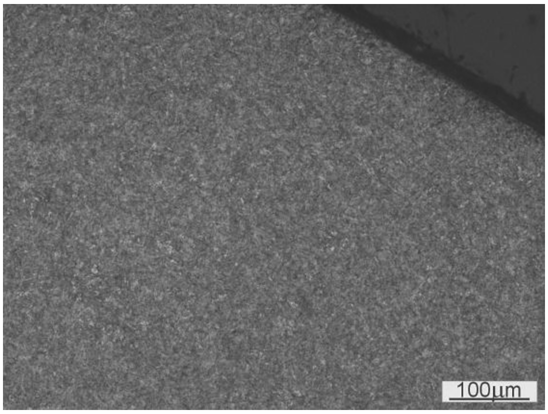


Fig. 15. Microstructure in the subsurface layer of investigated die (etched with 2% nital)

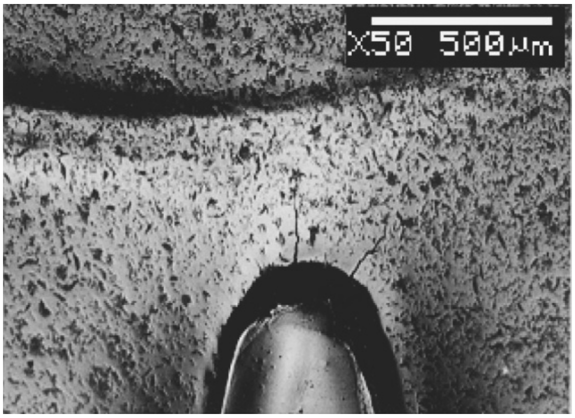


Fig. 16. Surface cracks at edge of identification mark [14]

One of the surface cracks, presented in Fig. 6a, originated at edge of the cooling hole, as it is shown in Fig. 18.

Such microstructural banding, as observed in investigated steel (Fig. 8-13), is acceptable, according to the North American Die Casting Association standard [15] but could promote crack propagation, regardless of very low fracture toughness, as it was revealed in the work [11]. SEM studies by use of scanning electron microscope Hitachi SU-70 revealed brittle fracture mode of observed surface cracks, as it shown in Fig. 19.

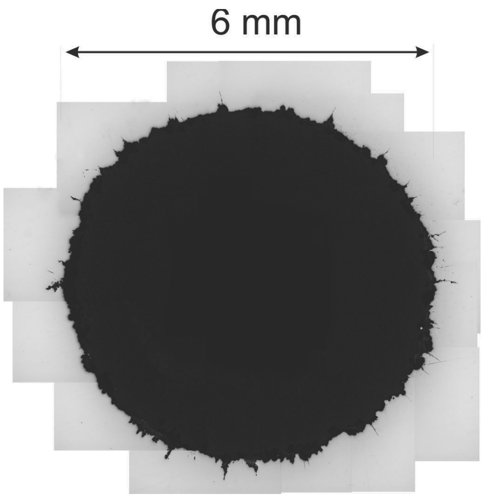


Fig. 17. Cracks nucleation at edge of cooling hole

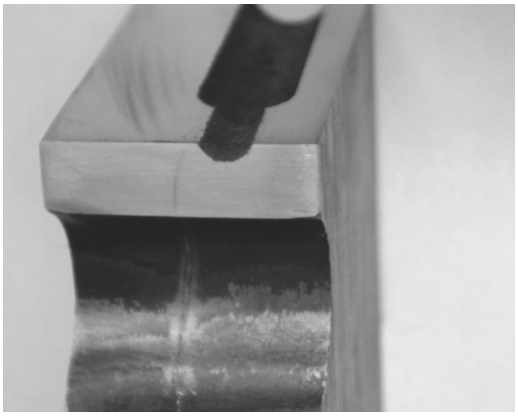


Fig. 18. Propagation of crack originated at edge of cooling hole

In order to determine if microstructural directionality could cause nonisotropic dilatation of die, and subsequently effect on crack propagation, thermal expansion coefficients were determined in the temperature ranges 30 - 100°C, 30 - 200°C, 30 - 300°C, 30 - 400°C, 30 - 500°C and 30 - 600°C as it is presented in Table 1 and shown graphically in Fig. 20.

From the basic die material properties point of view, the thermal expansion coefficient ought to be low to get low thermal stresses and avoid heat check cracking. As it is shown in Table 1 and Fig. 20, a thermal expansion coefficient of investigated die showed a strong dependence upon the specimen orientation with respect to the microstructural banding direction. Such considerable differences in values of thermal expansion coefficient between values for X-axis and both Y and Z-axis could play significant role as an additional factor determining the cracks direction (parallel to the X-axis).

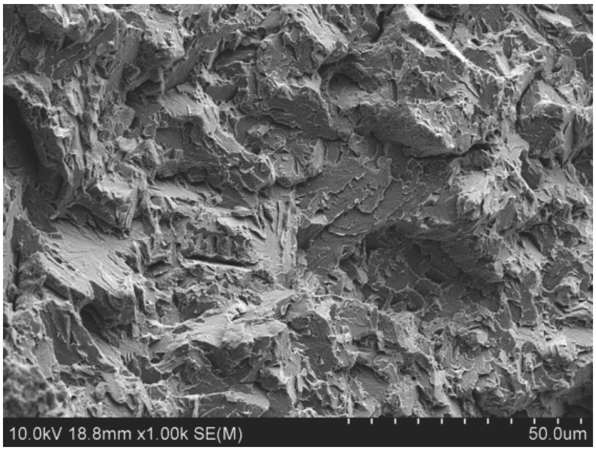


Fig. 19. Brittle fracture mode of observed surface crack (SEM)

Table 1.
Thermal expansion coefficients values

Temperature range, °C	Thermal expansion coefficient, $K^{-1} \cdot 10^{-6}$ along axis:		
	X	Y	Z
30-100	8.2	10.4	9.9
30-200	11.7	12.3	12.1
30-300	12.9	13.2	13.2
30-400	13.6	13.7	13.9
30-500	14.1	14.1	14.4
30-600	14.4	14.5	14.8

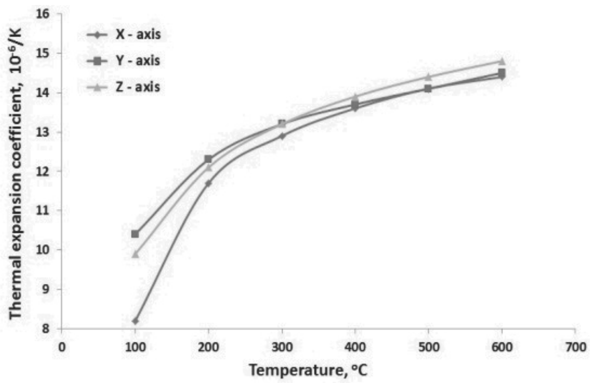


Fig. 20. Thermal expansion coefficient versus sample orientation

4. Conclusions

As it was revealed in work [11], the very low fracture toughness of investigated die for aluminium alloy die-casting has an essential influence on the premature failure of die. Regardless of this, in the present work it was shown that the differences in the values of thermal expansion coefficient, determined along the three axes of the coordinate system, promote cracks propagation according to the microstructural banding direction.

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