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Surface wear of steel X38CrMoV5-1 in conditions of die casting

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Abstract: Previous research in area of high-pressure die casting mould surface wear has led to conclusions shown in this paper. Most significant wear parameters are defined according to previous research. Led by these conclusions, a machine was designed which is capable of simulating similar work conditions of the mould material surface. This paper presents four differently treated samples. All samples were manufactured from steel X38CrMoV5-1 which is commonly used for high-pressure die casting moulds. Two samples were heat treated by spheroidize annealing. One was quenched and tempered at high temperature. The other one was also treated by quenching and high temperature tempering and then nitrided. Quenching, tempering and then nitriding are common heat treatment procedures of mould material used for high-pressure die casting. The results, after 10000 and 32000 testing cycles, are presented in this paper.

Izvorni znanstveni rad

Sažetak: Dosadašnje istraživanje u području trošenja površine materijala kalupa za visokotlačno lijevanje aluminijskih legura dovelo je do zaključaka o najutjecajnijim parametrima ovakvog procesa lijevanja na trošenje površine kalupa. Vodeći se ovim zaključcima dizajniran je uređaj za ispitivanje koji je sposoban simulirati uvjete rada površine materijala kalupa. U ovom radu ispitana su 4 uzorka u različitim početnim stanjima. Svi uzorci izrađeni su od čelika X38CrMoV5-1 često korištenog za izradu kalupa za visokotlačno lijevanje aluminijskih legura. Dva uzorka su u omekšanom stanju, jedan je obrađen toplinskom obradom poboljšavanja a jedan je poboljšan i zatim nitriran, kao što se često izvodi sa materijalom stvarnog kalupa. Prikazani su rezultati ispitivanja nakon 10000 i 32000 ciklusa ispitivanja.

1. Introduction

This paper presents the preliminary research of mould surface wear as a part of project "Optimisation and modelling of thermal processes of materials". The project is funded by Croatian Science Foundation. Most influential wear mechanism of mould surface of high-pressure die casting process is thermal fatigue. Erosion and adhesive wear or soldering have a high impact on surface wear [1, 2]. When the molten casting alloy is in contact with the mould surface, the surface material is heated and expands. The heat is conducted through the massive mould and the surface is cooled, which leads to contraction of the material on the surface. The greater the difference between the mould temperature and the molten alloy, the larger is the expansion and contraction of the surface which causes cracks to occur sooner [2]. When the yield strength of the material was exceeded near the surface, local accumulation of plastic deformation occurs, that leads to initial cracks. Propagation of initial crack leads to detachment of material from the surface [3, 4, 5]. Difference between mould temperature and molten aluminium temperature will be reduced by increasing moulds preheating temperature. Therefore, mould preheating temperature directly affects the occurrence and propagation of thermal fatigue cracks.

While filling the mould, molten alloy reaches speed up to 60 *m/s* [6, 7]. Erosion wear is additionaly increased by presence of hard particles in molten alloy. For example, Al_2O_3 particles have high hardness (2000 *HV*) and high melting temperature (2072 *°C*). Erosion wear is most intense on surfaces where molten alloy firstly reaches mould surface [8]. Previous scientific research has shown that erosion wear with hard particles has the greatest effect with smaller angles of impact (around 30°) [9]. Therefore, when considering erosion wear of mould surface for high-pressure die casting, the most influential wear mechanism is abrasion. It was shown that increasing the mould temperature, erosion wear increases but thermal fatigue wear decreases [9]. Application of hard coatings with metal carbides or nitrides can significantly increase resistance to erosion wear [7].

Because aluminium has high affinity toward iron from the mould steel, soldering of the casting alloy with the surface of the mould may occur. Soldering occurs in the case the lubricating agent was washed out by the molten alloy. At increased temperatures, intermetallic bonds form between aluminium from the casting alloy and iron from the steel mould [10, 11]. Therefore, aluminium corrodes the mould material on the surface by reacting with iron. Combined with erosion, it can cause significant loss of material on the mould surface. Erosion aggravates soldering of the casting alloy on the mould surface, which enhances adhesion wear [8, 12]. According to other research, aluminium alloy temperature had a significant effect on mould wear. Increasing the molten aluminium alloy temperature, results in increased adhesion wear but reduced erosion wear [13]. Formation of intermetallic bonds can be significantly reduced by applying various types of coatings and surface modifications [7, 14]. High-pressure die casting mould surface wear examples are shown on figure 1.

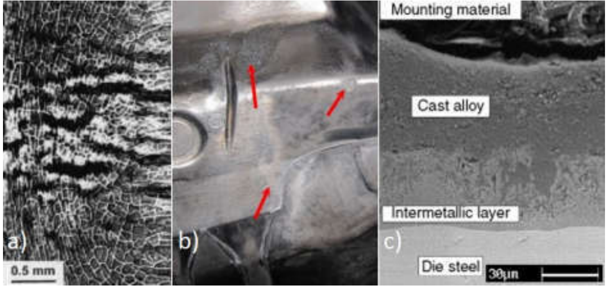

Figure 1. Wear mechanisms examples: thermal fatigue (a), erosion (b) and adhesion (c) [15, 16, 17]

Slika 1. Primjer trošenja površine toplinskim umorom (a), erozijom (b) i adhezijom (c) [15, 16, 17]

2. Development of laboratory equipment

Ideally, the experiment would be done on the high-pressure die casting machine but this kind of experiment would be very expensive. Review of previous research led to conclusion that there is an interaction between wear mechanisms that influence the total mould surface wear [2, 13, 18]. Testing of wear should be done on a testing device which takes in consideration most of the influential parameters, so the conditions of testing would be as similar as possible as real conditions. It is desirable to use casting aluminium alloy that is used in real processes to simulate the heat transfer as real as possible, and to achieve the ability to test erosion and adhesion wear. To reduce soldering of aluminium alloy on mould surface and to make the testing more relevant, it is necessary to use a lubricant. Lubricants that are usually used in these processes are based on molybdenum disulphide, graphite and hexagonal boron nitride.

Thermal fatigue wear mechanism is not evident in most of previous research because it does not occur at small number of testing cycles [19]. For corresponding test effects of all wear mechanisms, testing device must have a capability to execute a large amount of testing cycles. It is also necessary to have the possibility to test the effects of different impact angles of molten aluminium, considering previous research showed that angle of impact has a significant effect on wear [9]. For testing material, a hot work steel which is commonly used for high-pressure casting should be used (H10, H11, H13). Except this, it should be possible to vary the mould preheat temperature, relative speed between the sample and molten aluminium during contact, molten aluminium alloy temperature, lubricant, casting alloy, sample material, sample material heat treatment, coating and surface modification. These parameters influence the total amount of wear and should be tested.

Under these conditions, a testing device is designed. When designing the device, goal was to simplify testing, reduce testing costs, speed up the testing process and enable a high number of testing cycles. Testing was done by immersing the sample, made from mould material, in molten aluminium casting alloy. After leaving the molten alloy, sample is immersed in the lubricant. Mould temperatures are simulated and adjusted by holding times in molten aluminium alloy and lubricant. Wear is measured by weighing the samples on a Mettler B5 scale with accuracy of ±0,0001 *g*. Erosion was tested by varying the sample speed on impact with molten aluminium alloy. Motions are achieved by servo motor Kollmorgen AKM54K-ACDNCA-00. Arm which holds the sample is 200 *mm* long so a high circumferential speed can be achieved using a relatively small angle for acceleration. Motion of the servo motor was programmed in BASIC computer language. Motor is controlled by Kollmorgen AKD-T01207-NBAN-E000 servo drive. Aluminium alloy is melted by 650 *W* heaters. Temperature of the molten aluminium alloy is controlled by a type K theromelement (NiCr-Ni). Regulation of the temperature was done by Novus N480D controller. Sample temperature after exiting the molten aluminium alloy and lubricant was controlled by ScanTemp 480 infrared thermometer. Testing device is shown on figure 2.

Figure 2. Testing device

Slika 2. Uređaj za ispitivanje

3. Laboratory experiment

This preliminary testing was done on samples made from X38CrMoV5-1 material. This is a hot work tool steel (H11). Chemical composition of the material is given in table 1. Samples were made on a five-axis CNC machining center MAHO. Cross section shape is a symmetrical NACA 0012 profile (National Advisory Committee for Aeronautics). This profile was chosen because of its low drag coefficient. The goal is to reduce resistance on impact and when moving through molten aluminium. Dimensions of the sample are 10x58x4 *mm*. Part of the sample used for testing is 40 *mm* in height and 2,5 *mm* thick. Samples after machining and nitriding are shown in figure 3.

Table 2. Chemical composition of testing steel X38CrMoV5-1

Tablica 2. Kemijski sastav korištenog čelika X38CrMoV5-1

C, %	*Si, %*	*Mn, %*	*Cr, %*	*Mo, %*	*Ni, %*	*V, %*
0,39	0,97	0,43	5,01	1,14	0,21	0,45

All samples have the same shape and were made from the same material. Two samples (69 and 70) are heat treated by spheroidize annealing. Their hardness is 221 *HV*. One was quenched in oil from 1050 *°C*. Hardness after quenching of the sample was 564 *HV*. Then it was tempered three times on high temperatures (sample 15).

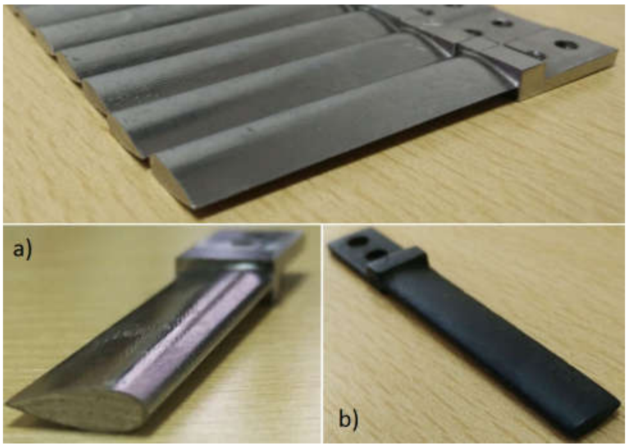

Figure 3. Samples for testing after machining (a) and nitriding (b)

Slika 3. Uzorci za ispitivanje nakon strojne obrade (a) i nitriranja (b)

Hardness after tempering was 480 *HV*. Second sample was treated the same way, but also nitrited in salt bath with holding time of 4 *h* on temperature 580 *°C* (sample 14). Hardness of nitrided sample was 1100 *HV*.

One testing cycle is consisted of heating the sample in molten aluminium alloy, then cooling in the lubricant. Aluminium alloy AlSi9Cu3(Fe) was used in molten state at constant temperature of 675 *°C*. Lubricant used for testing was molybdenum disulphide (MoS_2). MoS_2 particles are transferred in oil that is dispersed in water (1:80 ratio). Circumferential impact speed of the sample was set to 10 *m/s*. After holding the sample in molten aluminium alloy for 0.5 *s*, the sample heated up to 220 *°C*. Immersing the sample in the lubricant and holding it for 0,2 *s* cools the sample to 50 *°C*. One test cycle time is 4 *s*.

4. Results and analysis

On samples 14, 15 and 69 testing was done for 10000 cycles according to the previous parameters. After removing from the testing device the samples were cleaned by immersion in a NaOH solution (20%). The goal is to remove soldered aluminium alloy and other impurities from the surface to have accurate weight loss wear results. Then the samples were weighted. The results are shown in figure 4. Unexpectedly, most weight loss was on the nitrided sample. Wear of quenched and tempered sample was less than wear of sample treated by spheroidize annealing. Samples are shown on figure 5, after testing, before immersion in NaOH solution.

Figure 5 shows that nitrided sample (14) was significantly damaged on the sharp edge of the sample. This indicated the problem of the brittle nitrided layer when nitriding areas of small radius of curvature. There is no soldered aluminium alloy on this sample because the nitrided layer prevents reaction between iron from the mould steel and aluminium from the casting alloy. Therefore, there are no intermetallic bonds and adhesion wear [20].

Heat treated sample (15) was worn significantly less because of the high initial hardness. As it was not nitrided, the sharp edge of the sample was minimally damaged. There was no protective layer that could prevent formation of intermetallic bonds. Soldered aluminium alloy can be seen on the sample.

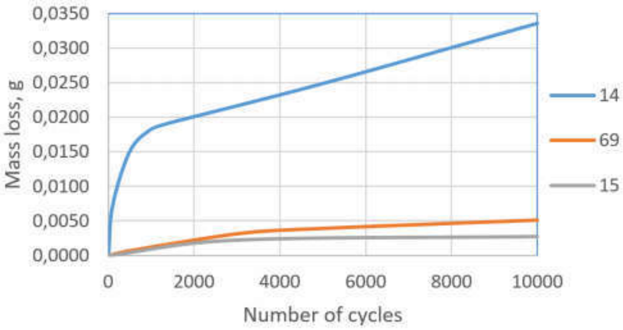

Figure 4. Mass loss of samples

Slika 4. Gubitak mase uzoraka

Figure 5. Samples 14, 15 and 69 after testing

Slika 5. Uzorci 14, 15 i 69 nakon ispitivanja

Sample treated by spheroidize annealing (69) was damaged more than the quenched and tempered sample (15) because of the significantly less initial hardness. There was a significant amount of soldered aluminium alloy on the sample also.

Thermal fatigue did not manifest using these testing parameters and 10000 test cycles. Therefore, testing of the final sample treated by spheroidize annealing (70) was done by different parameters to achieve thermal fatigue. Maximum temperature was increased to 350 *°C* by holding the sample in molten aluminium alloy for 6 *s*. Then the sample was cooled in the lubricant (MoS_2) for 2 *s* which lowered the temperature to 70 *°C*. After 32000 test cycles, a characteristic thermal fatigue network of cracks appeared on the surface. Some cracks caused by thermal fatigue could be seen on the edges of the sample too. The sample also had a significant amount of soldered aluminium alloy. Surface of the sample after 32000 test cycles is shown on figure 6.

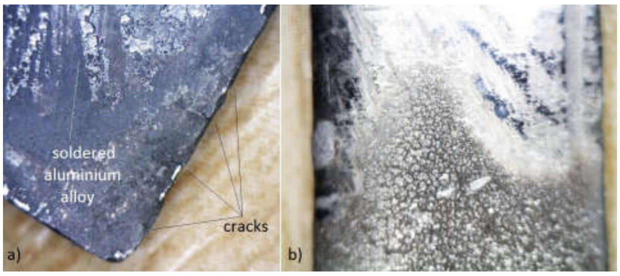

Figure 6. Sample 70 after testing, before (a) and after cleaning(b)

Slika 6. Uzorak 70 nakon ispitivanja, prije (a) i poslije čišćenja (b)

5. Conclusion

There was less wear for quenched and tempered sample (15) than for sample treated with spheroidize annealing (14) because higher initial hardness lowers accumulation of plastic deformation on the surface layer [21]. Therefore, high initial hardness improves resistance to thermal fatigue wear of the material.

Most significant wear was in the case of nitrided sample. It was mostly at the sharp edge of the sample. On the edges, during the nitriding process, nitrogen diffuses from all angles and causes oversaturation of nitrogen [22]. If this is not controlled, a network of iron nitrides will form at the edges. This network forms at the grain boundaries. The result is a very brittle surface and premature cracks or removal of material from the surface.

Thermal fatigue was not noticeable before 32000 test cycles. Therefore, further testing has to be done with high number of test cycles, to correctly determine the effect of thermal fatigue wear mechanism. Most influential parameters for thermal fatigue wear are the preheating temperature of the mould and relative speed between the mould and casting alloy. These parameters will be varied in further experiments to determine their effect and interaction.

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