THERMAL WEAR BEHAVIOUR OF H13 TOOL STEEL IN DIE CASTING PROCESS

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Doctor of Philosophy

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy in Mechanical Engineering.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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LIST OF SYMBOLS

ε_a	Alternating strain amplitude ($\mu m/m$)
ΔK_I	Alternating stress-intensity factor
λ	Coefficient of heat transfer in the layers, $W/(m^2$ °C)
$C(t)$	Concentration of certain elements in the molten alloy at time t
k_C	Crack critical value
da / dN	Crack grow rate
N_i	Crack initiation (μm)
N_f	Critical crack (μm)
Region II	Cylindrical shape
P	Density, kg/m^3
T_{s_1}	Die surface temperature (^oC)
u	Displacement
D	Effective diameter of the channel *(mm)*
E	Elastic modulus (N/m^2)
α	Expansion for the linear thermal coefficient
k_{IC}	Fracture toughness ($MPa.m^{1/2}$)
T_h	Hot face temperature (^oC)
µ	Liquid metal viscosity, gram/(centimeter second) [$g/(cm .s)$]
ΔT	Magnitude of the temperature change (^oC)
n	Material specific exponent (-)
C_s	Maximum solubility of that element in the molten alloy
T_m	Mean die temperature (^oC)
ε_m	Mean strain (µm/m)
ε_{min}	Minimum strain (µm/m)
T_{s_2}	Minimum value temperature (^oC)
N	Number of cycles
Nu	Nusselt number ($Nu = hk / 1$)
$f(g)$	Parameter that depends on the size of the crack a
Pr	$Prandtl\ number = CpU / k$

υ	Poisson's ratio (-)
Re	$Reynolds\ number = vDp/\mu$
a	Size of the crack (µm)
Region I	Spherical shape (cylindrical with rounded end)
ε	Strain (µm)
$\Delta\varepsilon$	Strain range
R	Strain ratio (-)
K_s	Stress intensity factor
$T_{1\ surf}$	Temperature on the casting surface (^oC)
$T_{2\ surf}$	Temperature on the die surface (^oC)
T_∞	Temperature surrounding the fluid (^oC)
Q	The heat flux (W/m^2)
k	Thermal conductivity ($W/cm.^oC$)
K	Thermal fatigue resistance ($cm\ ^oC/W$)
V	Velocity of the metal(mm/s)
L	Width of insulation layers (mm)
ΔT	Magnitude of the temperature change (^oC)

LIST OF ABBREVIATIONS

AISI H13	American Iron and Steel Institute
ASTM	American Society for Testing and Materials.
ASTM	American Society for Testing and Materials.
CWRU	Case Western Reserve University
CVD	Chemical Vapor Deposition
CVD	Chemical Vapor Deposition
C.V. %	Coefficient of variation (*C.V*)
CNC	Computer Numerical Controlled
df	degree of freedom
DoE	Design of experiments
DX10	Design of Expert
EBSD	Electron backscatter diffraction
EDS	Energy Dispersive Spectrometer
(EDXS)	Energy-dispersive X-ray spectroscopy
FEA	Finite element model
HF	High Frequency
HPDC	High pressure die casting
PVD	Physical Vapor Deposition
PVD	Physical Vapor Deposition
PCVD	Plasma Chemical Vapor Deposition
εp	Plastic strain,
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
Std. Dev	Standard deviation
AISI H13	Steel 8407 Supreme, Malaysia
εT	Surface net thermal strain
Ra 2	Surface Roughness outcome
TRD	Thermal-Reactive Deposition and Diffusion
TCs	Thermocouples
TMF	Thermo-Mechanical Fatigue
$\alpha \Delta T$	Total thermal strain
ε_f	True fracture deformation

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ABSTRAK

Pendedahan peralatan acuan besi tuang dan proses penempaan kepada kitaran haba yang tinggi telah menyebabkan peningkatan tekanan serta mengakibatkan perubahan sifat permukaan bahan. Tesis ini membentangkan mekanisme kegagalan terma terhadap besi keluli AISI H13 yang digunapakai dalam proses besi tuang aluminum. Satu sistem kawalan kegagalan terma telah dibangunkan secara eksperimen dan simulasi proses besi tuang. Sistem ini terdiri daripada penebat relau berlapis dan sistem penyejukan yang terdiri daripada pengliran air secara konstant pada suhu 32 °C. Sampel adalah berbentuk rod silinder berdiameter 33 mm dan ketebalan dinding 6.5 mm. Sampel-sampel telah dicelup kedalam aluminum lebur pada suhu 700 ^{o}C dan seterusnya dicelup didalam air selama 24 saat untuk satu kitaran. Permulaan rekahan pada permukaan acuan dipengaruhi oleh perbezaan haba dan kekerasan besi tersebut. Satu reka bentuk eksperimen (DOE) telah dibangunkan untuk menganalisa kesan kekasaran permukaan dan parameter proses besi tuang terhadap sifat kegagalan terma. Selain itu, simulasi terma FEM telah digunakan untuk mengenalpasti peningkatan dan pengagihan suhu dipermukaan. Data eksperimen dinilai berdasarkan model metodologi respon permukaan (RSM). Ujikaji dijalankan dengan kitaran sebanyak 1,850, 3,000 and 5,000. Setiap sampel yang telah mengalami kegagalan terma telah dianalisa untuk kajian metalurgi, ukuran rekahan di permukaan dan karekter kekerasan. Sampel tersebut kemudiannya dianalisa secara optikal menggunakan Scanning Electron Microscopy (SEM), manakala analisa Energy Dispersive X-ray Spectroscopy (EDXS) dijalankan dikawasan rekahan pada permukaan sampel. Panjang rekahan dan profil kekerasan Vickers terhadap kegagalan terma dikenalpasti. Keputusan kajian metalurgi dan morfologi menunjukkan peningkatan rekahan seiring dengan peningkatan jumlah kitaran disebakan peningkatan tekanan haba pada jumlah kitaran yang tinggi. Saiz panjang rekahan pada sample hujung sfera (Region I) adalah 47 hingga 127 µm. Selain itu, kandungan oksigen pada jarak 140 µm daripada permukaan menunjukkan proses oksidasi telah berlaku. Pada suhu 700 ^{o}C, pembentukan aluminum oxide telah dikenalpasti pada permukaan sampel H13. Tekanan yang menyebabkan kegagalan terma dan sifat kekerasan adalah berbeza untuk dua jenis permukaan pada hujung sfera (Region I) dan bahagian silinder (Region II). Saiz rekahan pada Region I adalah lebih tinggi sebanyak 32 % berbanding Region II. Berdasarkan model, keputusan optimum adalah 26.5 µm untuk panjang rekahan, 3.114 µm untuk kasar permukaan dan 306 $HV_{0.5}$ nilai sifat kekerasan. Variasi antara data eksperimen dan data jangkaan daripada simulasi adalah kurang daripada 5 %, maka keputusan ini menujukkan model tersebut adalah sah. Kesimpulannya, sistem eksperimen dan simulasi bagi kegagalan terma dan permukaan bahan acuan besi tuang yang berpotensi tinggi telah dibangunkan dan disahkan.

ABSTRACT

During die casting, tools for die casting and hot forging applications are subjected to thermal cycles, which may induce high stress that always lead to plastic deformation. The interaction behaviour of these materials with the thermal and mechanical conditions are necessary to be studied through experimental and numerical simulation studies. The optimization of the samples thermo-mechanical conditions have formed the basis of several scientific studies. This study examined the thermal wear behaviour of A1S1 H13 steel, a conventional aluminum alloy die casting material when subjected to cyclic heating and cooling cycles. The experimental and simulation studies were effectively controlled via a thermal wear system that ensured a minimum heat loss from the furnace during the casting process. The quenching system provided a continuous water flow of 32 °C. Cylindrical samples of diameter 33 mm and wall thickness 6.5 mm were used. The samples were subjected to alternating heating (dipping in aluminum alloy at 700 °C) and cooling (at room temperature) cycles of 24 s intervals each. The die surface initiation and crack propagation were stimulated by thermal and hardness gradients acting on the contact surface layer. The effect of the machined surface roughness and die casting parameters on the thermal wear properties were studied via a developed design of experiment (DoE), while a FEM-based thermal simulation model was used for surface temperature generation and stress distribution at the studied temperatures. The experimental data were assessed on a thermo-mechanical wear life assessment model, assisted by response surface methodology (RSM). The testing was successively done at 1,850, 3,000, and 5,000 cycles. After each number of cycles, all the sample surfaces were visually inspected. The thermally-worn samples were characterized for metallographic, surface crack, and hardness characteristics. The samples were later segmented and analyzed through optical and scanning electron microscopy (SEM). Additionally, Energy Dispersive X-ray Spectroscopy (EDXS) was performed on the areas surrounding the cracks. The maximum crack length and Vickers hardness profile of the thermal wear cracks were obtained. The results of the metallographic and morphological studies indicate an increase in surface crack formation with an increasing number of cycles, suggesting an increase in thermal stresses at higher number of cycles. The crack length of the spherically-ended Region I was about 47 to 127 µm. Meanwhile, a high oxygen content was observed within 140 µm distances from the sample surface, which led to oxidation. At 700 ˚C, aluminum oxides formed and in contact with the H13 sample surface. These stresses propagate the thermal wear crack length into the tool material of differently-shaped Region I and cylindrically-shaped Region II, while a different case was observed for the hardness. The crack length of Region I was about 32 % higher than that of Region II, while a different case was observed for the hardness. Based on the model, the best results were achieved at an optimal condition of crack length 26.5 µm, surface roughness 31.14 µm and hardness property 306 $HV_{0.5}$; showing that the RSM effectively related the wall thickness, machine surface roughness, and immersion time to the responses. The variation between the experimental and predicted simulation data was less than 5 %, showing the validity of the model. In conclusion, an effective experimental and simulation system for the determination of the thermal wear and surface failure of die materials in real die-casting environments was developed and validated. Similarly, the relationship between the machined surface roughness, wall thickness, and immersion time of the AISI H13 tool with its thermal wear formation was established.

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